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Title: Exotic hadrons in dense QCD systems

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Exotic hadrons in dense QCD systems

Matt Durham
durham@lanl.gov

Florida State Colloquium
14 Oct 2021

Outline

- Conventional quarkonium - $Q\bar{Q}$ bound states
  - Simple quantum mechanical system
  - Interactions with a hadronic medium

- Exotic quarkonium - multiquark states
  - Few examples
  - Detailed look at X(3872) and $\boldsymbol{T_{cc}^{+}}$ in medium

- Outlook: future measurements
  - Fixed-target collisions at the LHC
  - Electron-Ion Collider

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Quark Model of Hadrons

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

8182/TH.401
17 January 1964

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}$AAAA, $\bar{A}\bar{A}$AAAAA, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}$A, $\bar{A}\bar{A}$AA etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}$A and AAA, that is, "deuces and treys".

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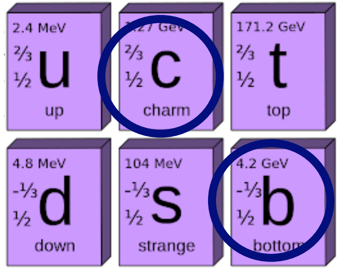
Mesons: $q\bar{q}, qq\bar{q}\bar{q}, qqq\bar{q}\bar{q}\bar{q}, \ldots$

Baryons: $qqq, qqqq\bar{q}, qqqqq\bar{q}\bar{q}, \ldots$

Hadrons with >3 quarks have been expected since the very beginning.

Heavy quark production at colliders



Heavy quarks: charm and bottom

Mass $\gg \Lambda_{QCD}$, perturbative methods applicable

Not present in incoming beam particles

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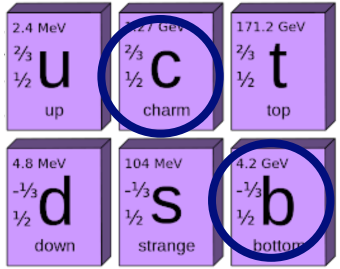

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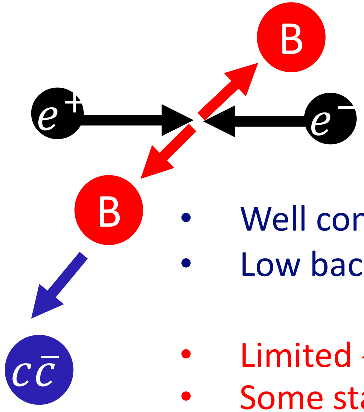
Electron-positron colliders (B factories)

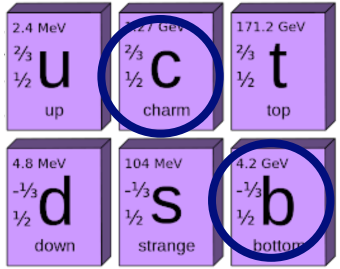
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$



- Well constrained initial state
- Low backgrounds

- Limited $\sqrt{s}$ range
- Some states difficult to access

Heavy quark production at colliders



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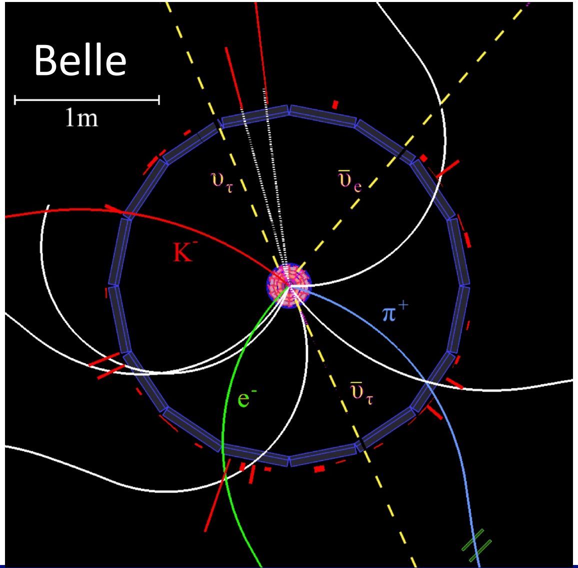

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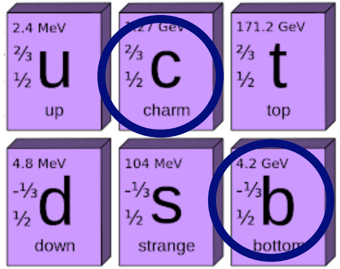

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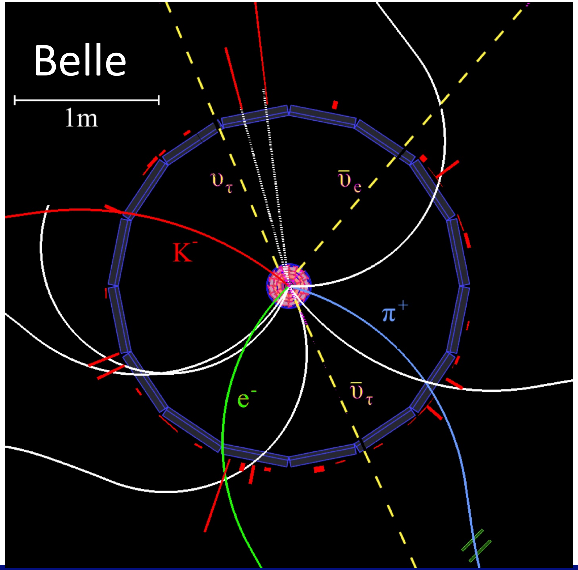
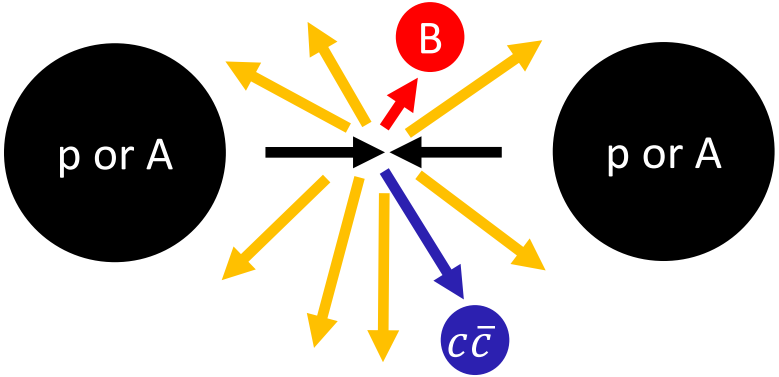
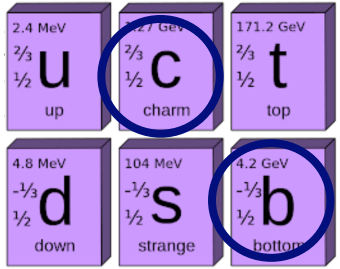


Hadron colliders (e.g. RHIC, Tevatron, LHC)



- High $\sqrt{s}$, large total cross section
- Access to wide range of states
- Initial state (parton+parton) not entirely constrained
- **Interactions among produced particles become important**

Heavy quark production at colliders



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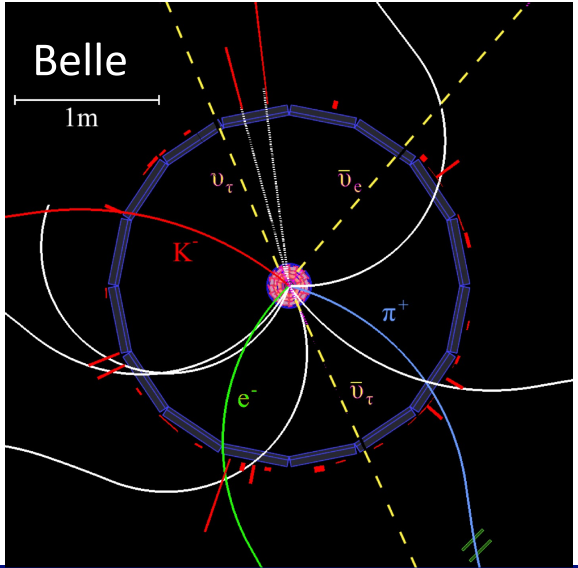

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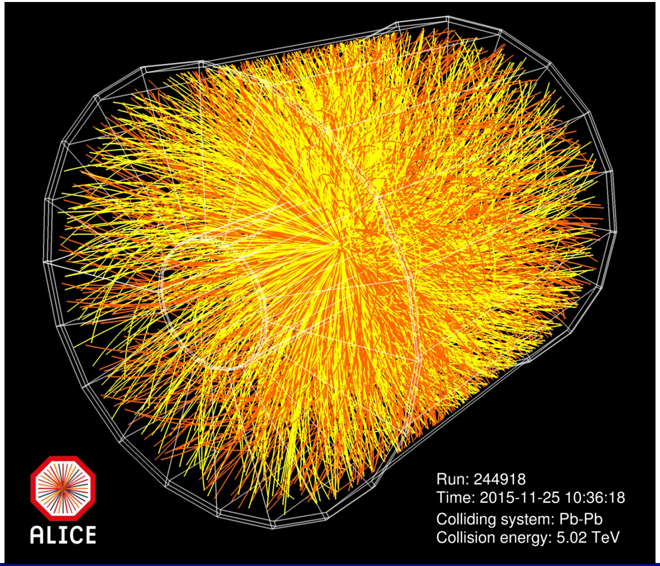

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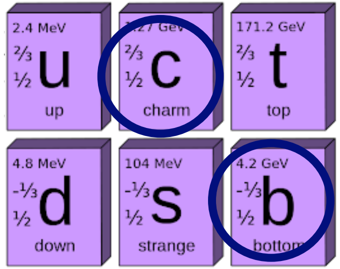

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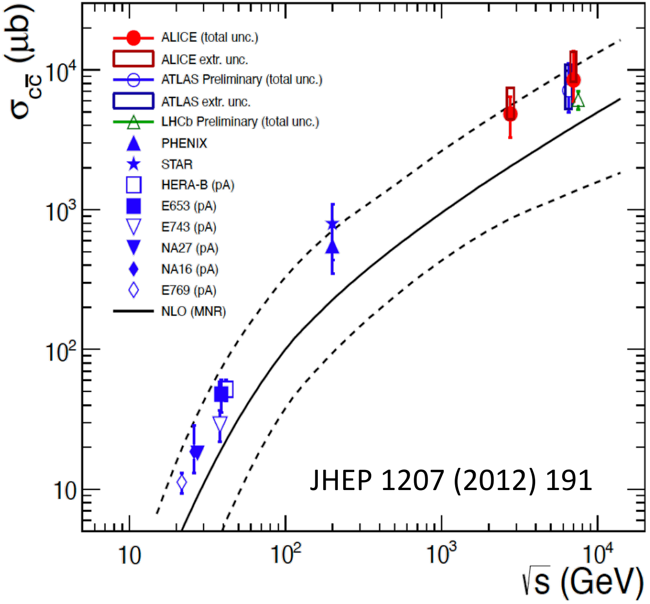
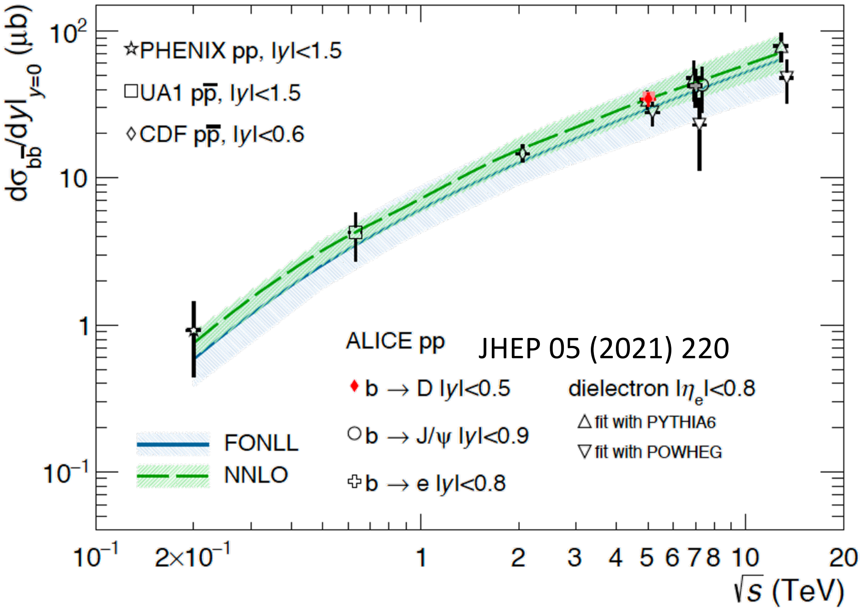
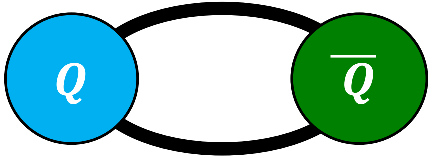




Quarkonia – bound states of heavy quarks



Solve Schrodinger equation with the potential

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

Phys. Rev. D 72, 054026 (2005)

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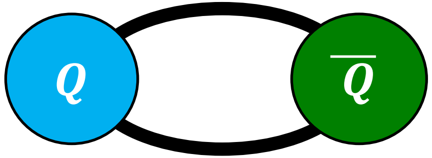

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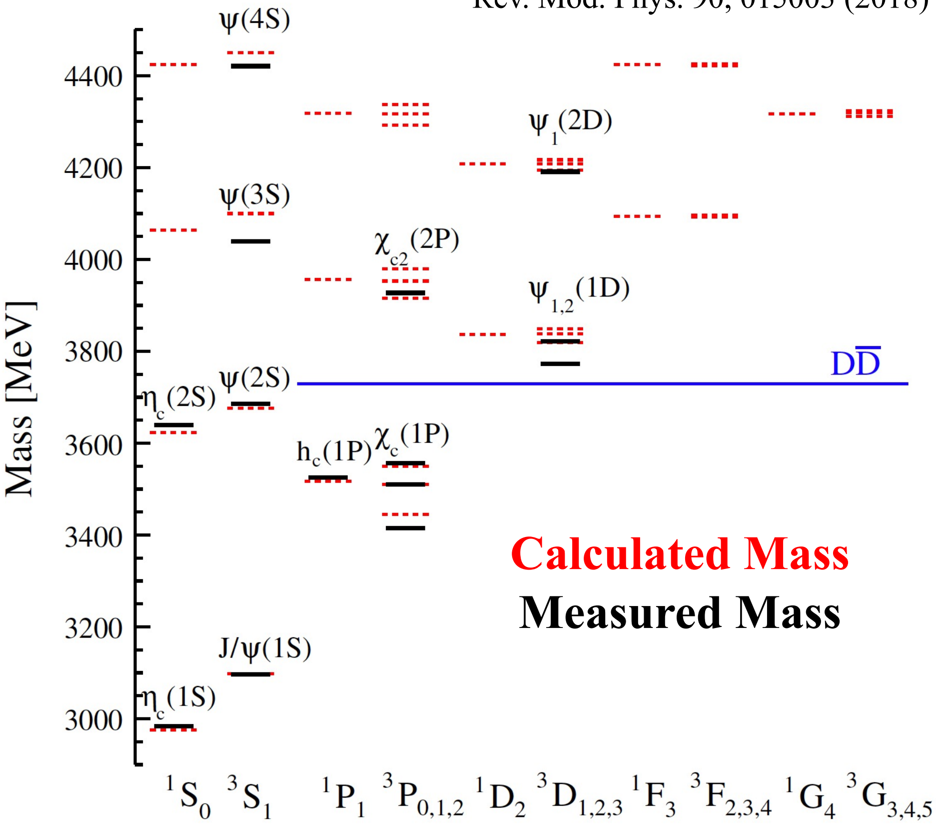

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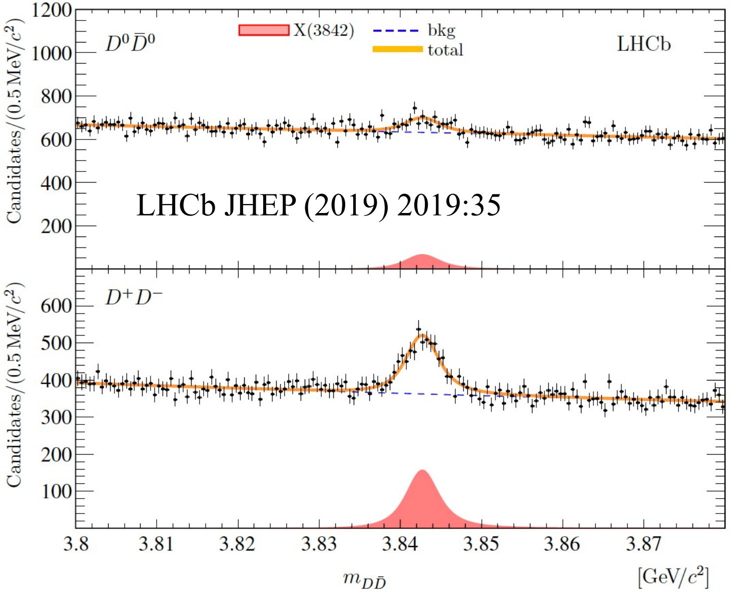

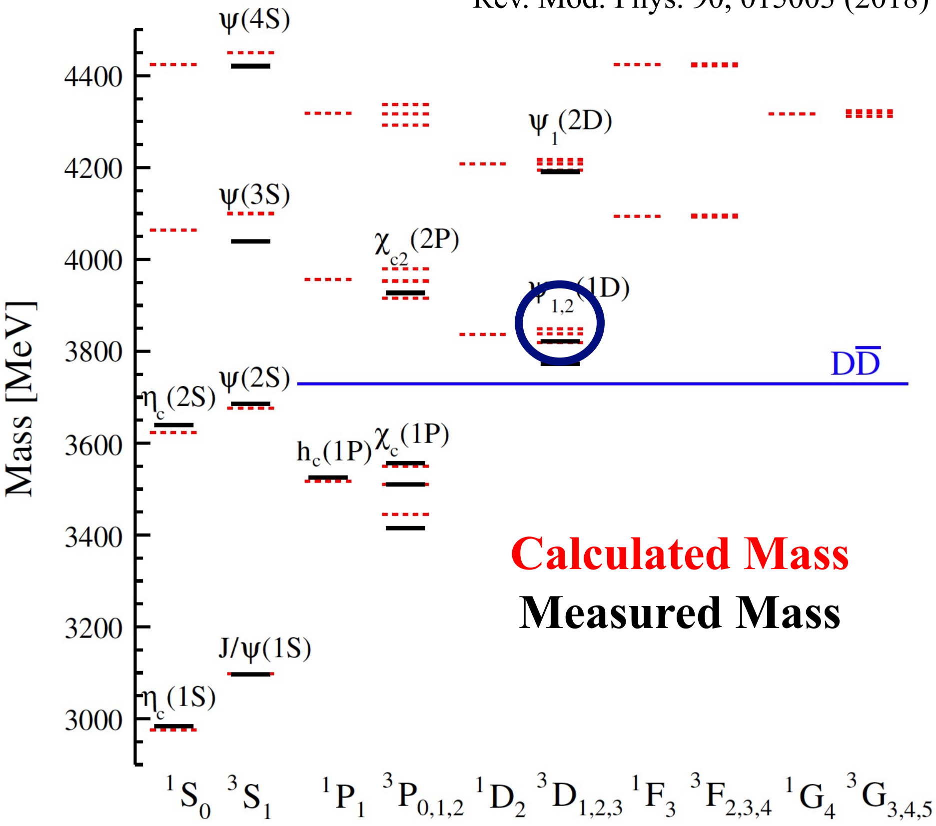

The most recently discovered charmonium state: $\psi_3(1^3D_3)$

Measured mass: 3842.71 ± 0.16 ± 0.12 MeV
Predicted mass: 3849 MeV

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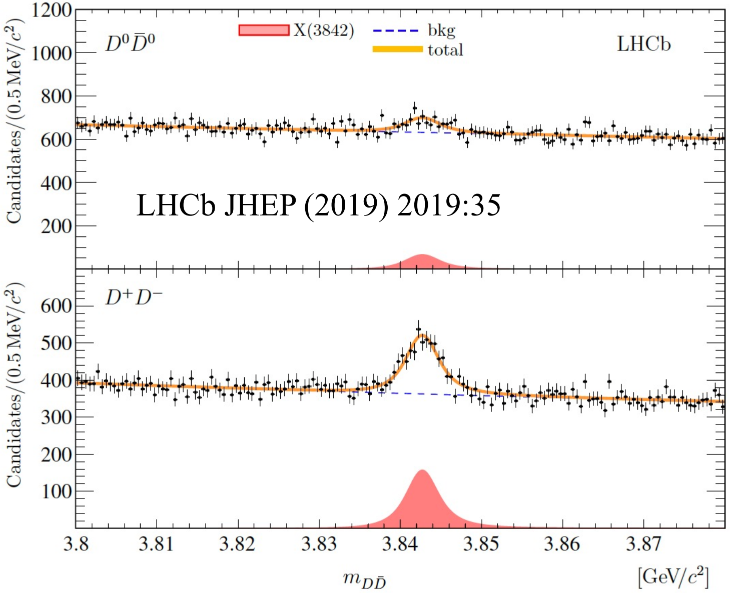

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Incredibly rich structure, accessible theoretically and experimentally

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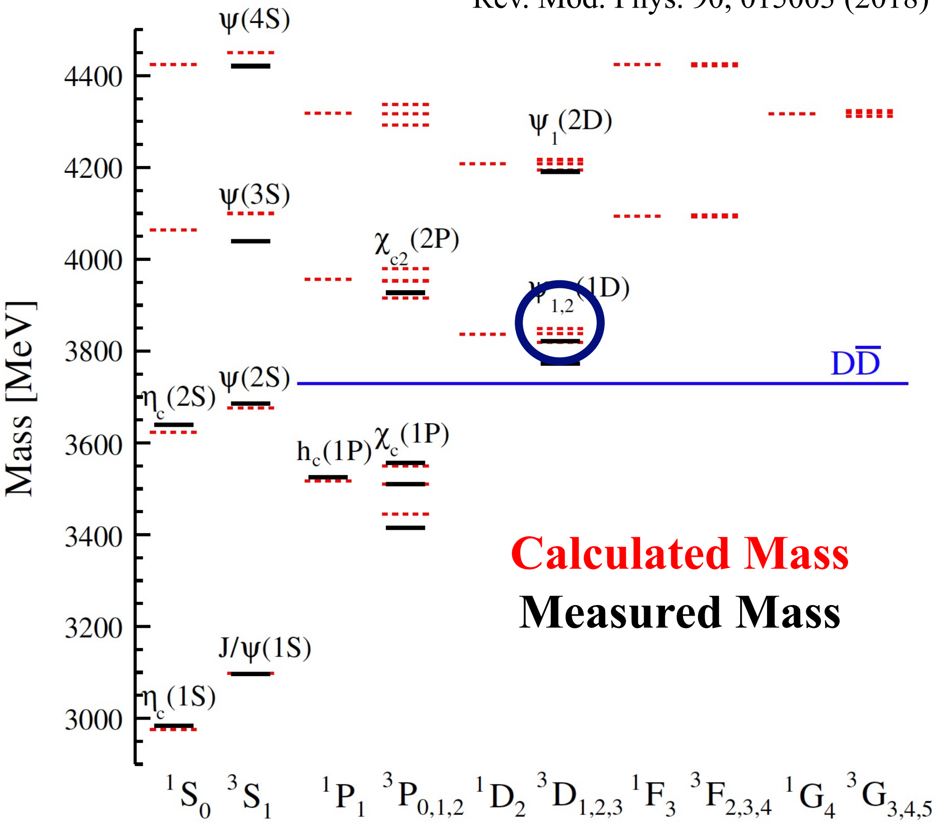
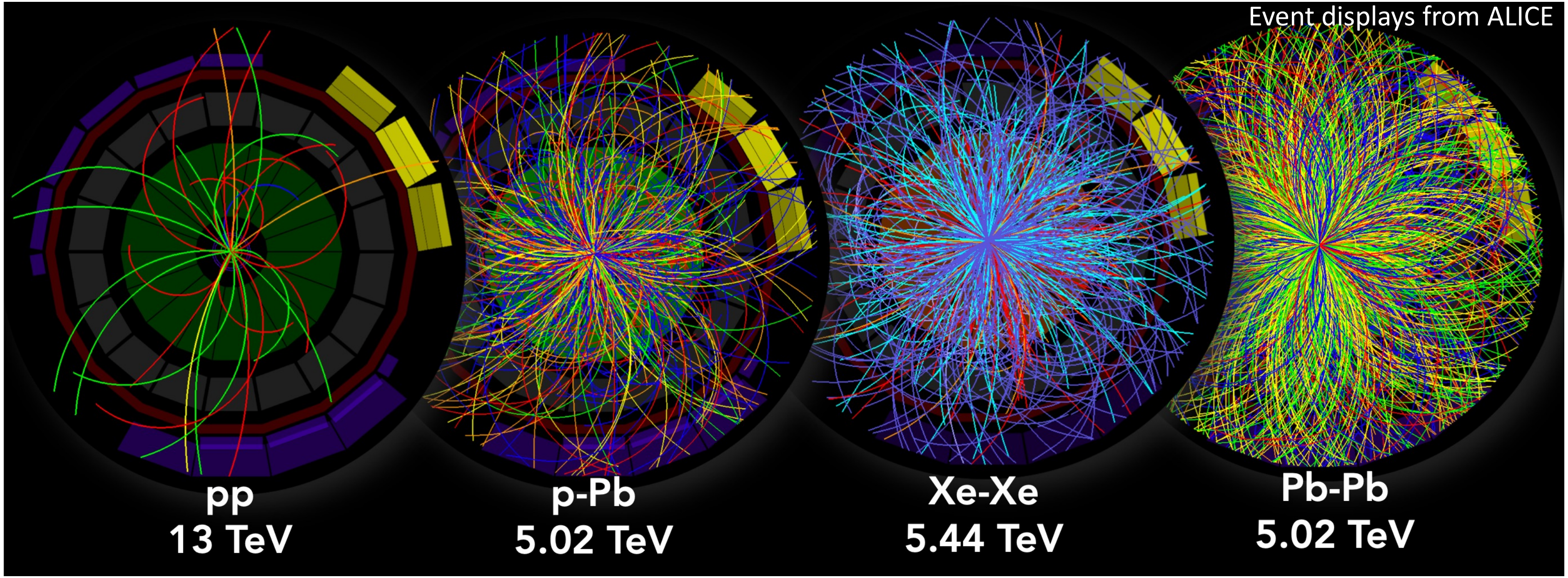


The QCD medium

Diffuse medium (pp,pA) → Increasing T, $N_{charged}$ → Dense medium (pA, AA)

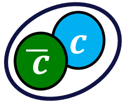
- Use (mostly) understood quarkonia states to as a calibrated probe of non-perturbative effects in dense many-body hadronic systems.



Quarkonia in the QCD medium

$\boldsymbol{J/\psi(1S)}$

$E_b \approx 600\ MeV$



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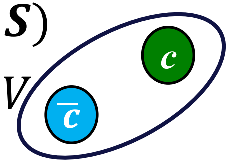

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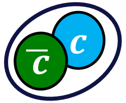

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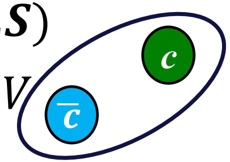

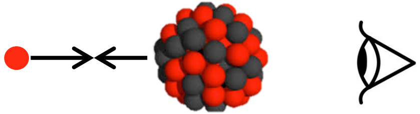

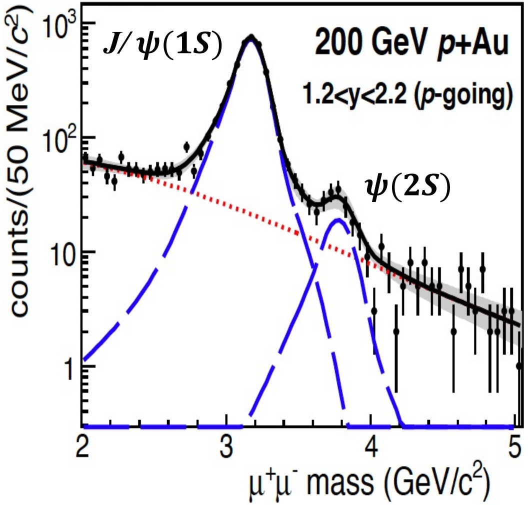

Relatively *low* particle density

Quarkonia in the QCD medium

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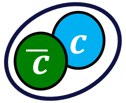

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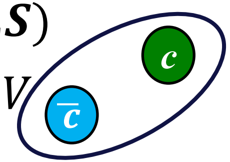

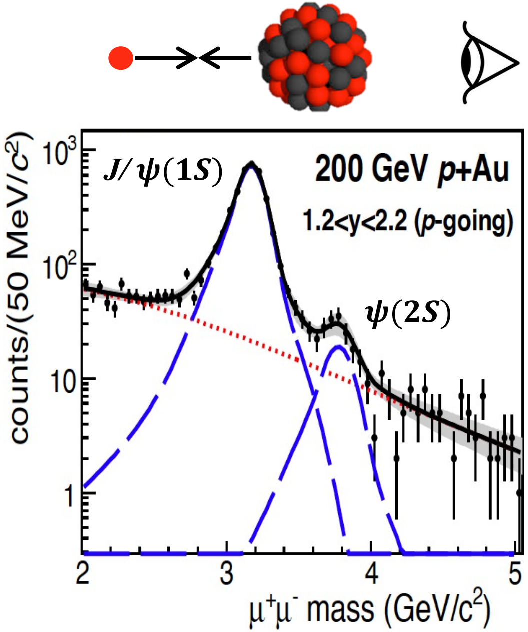

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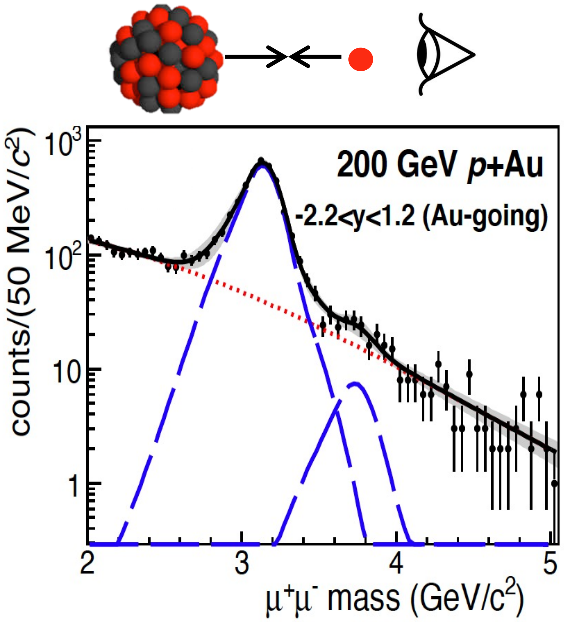

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Quarkonia in the QCD medium

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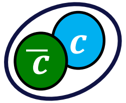

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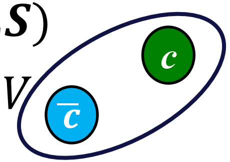

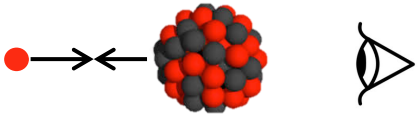

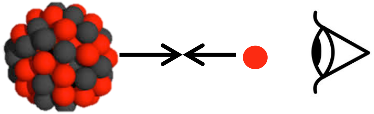

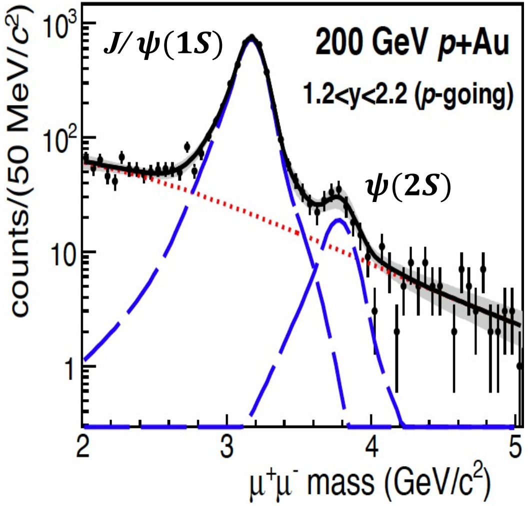

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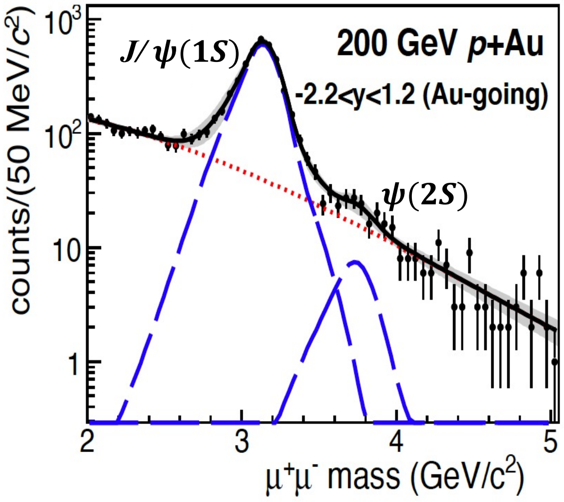

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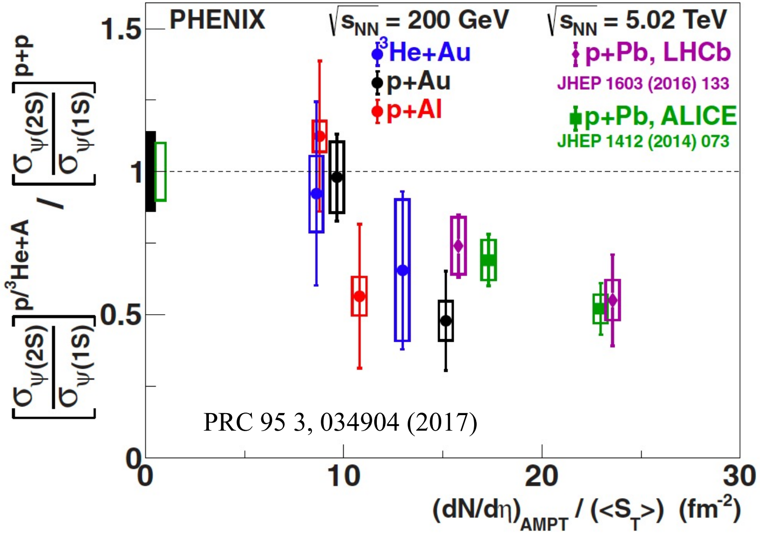
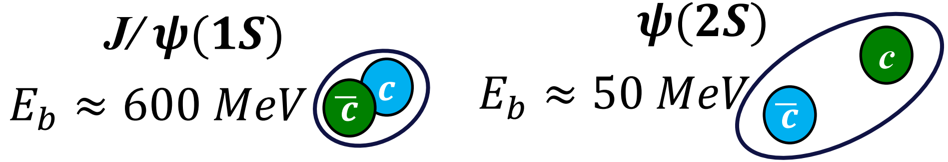
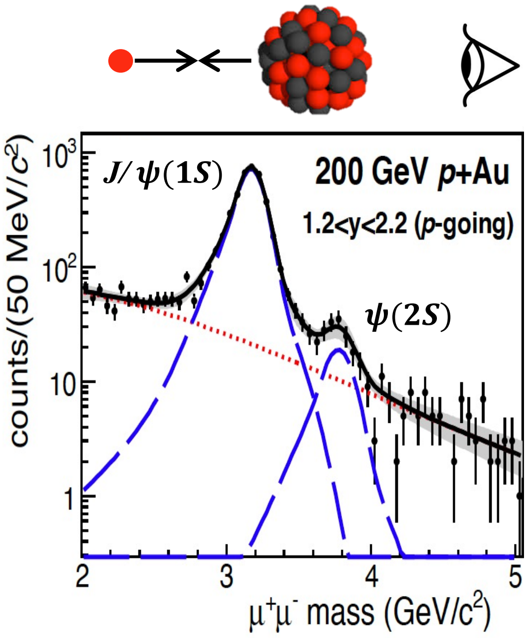


Quarkonia in the QCD medium





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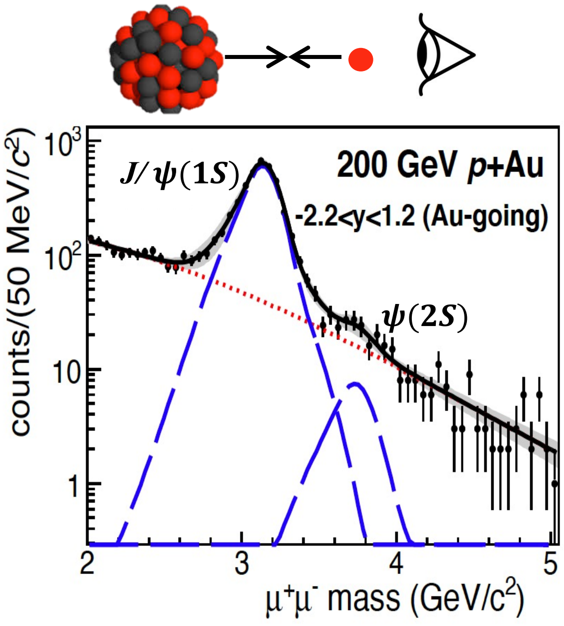

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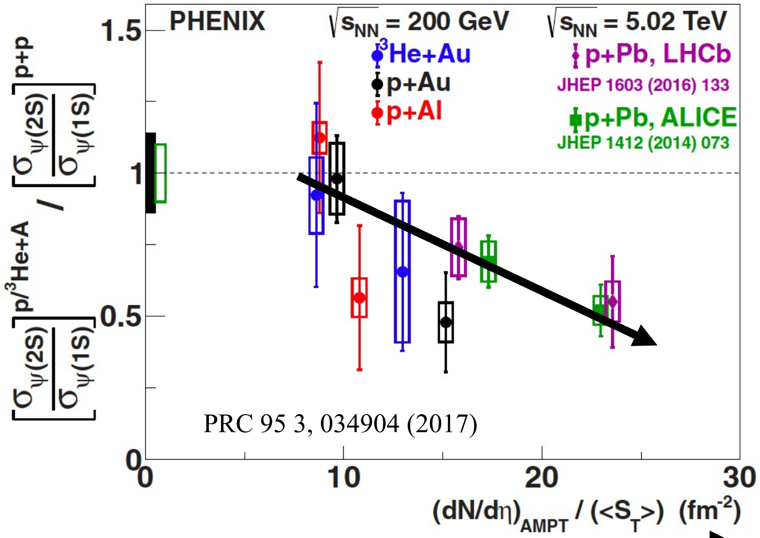
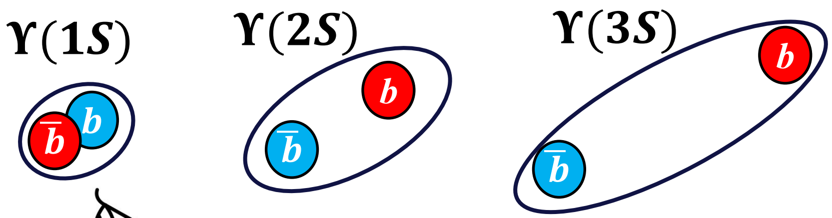
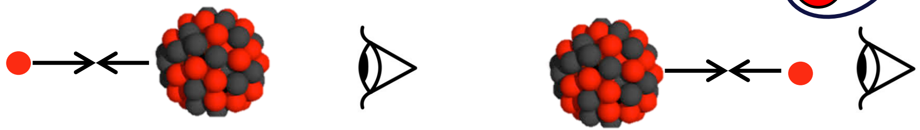
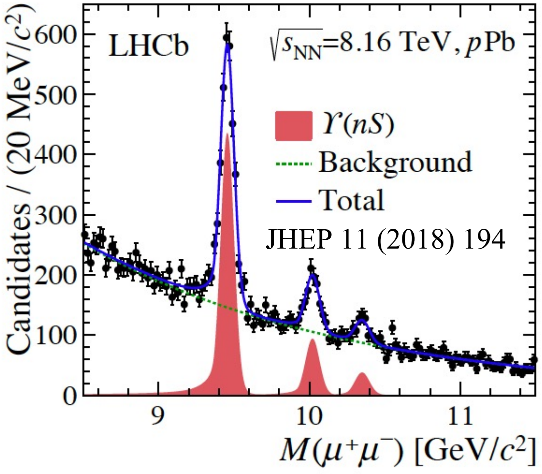


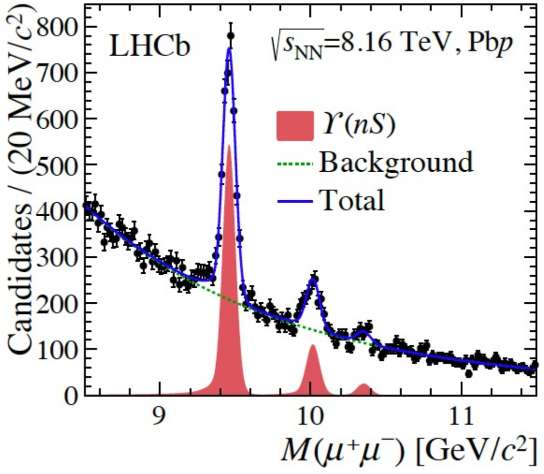
Increasing charged particle density

Quarkonia in the QCD medium









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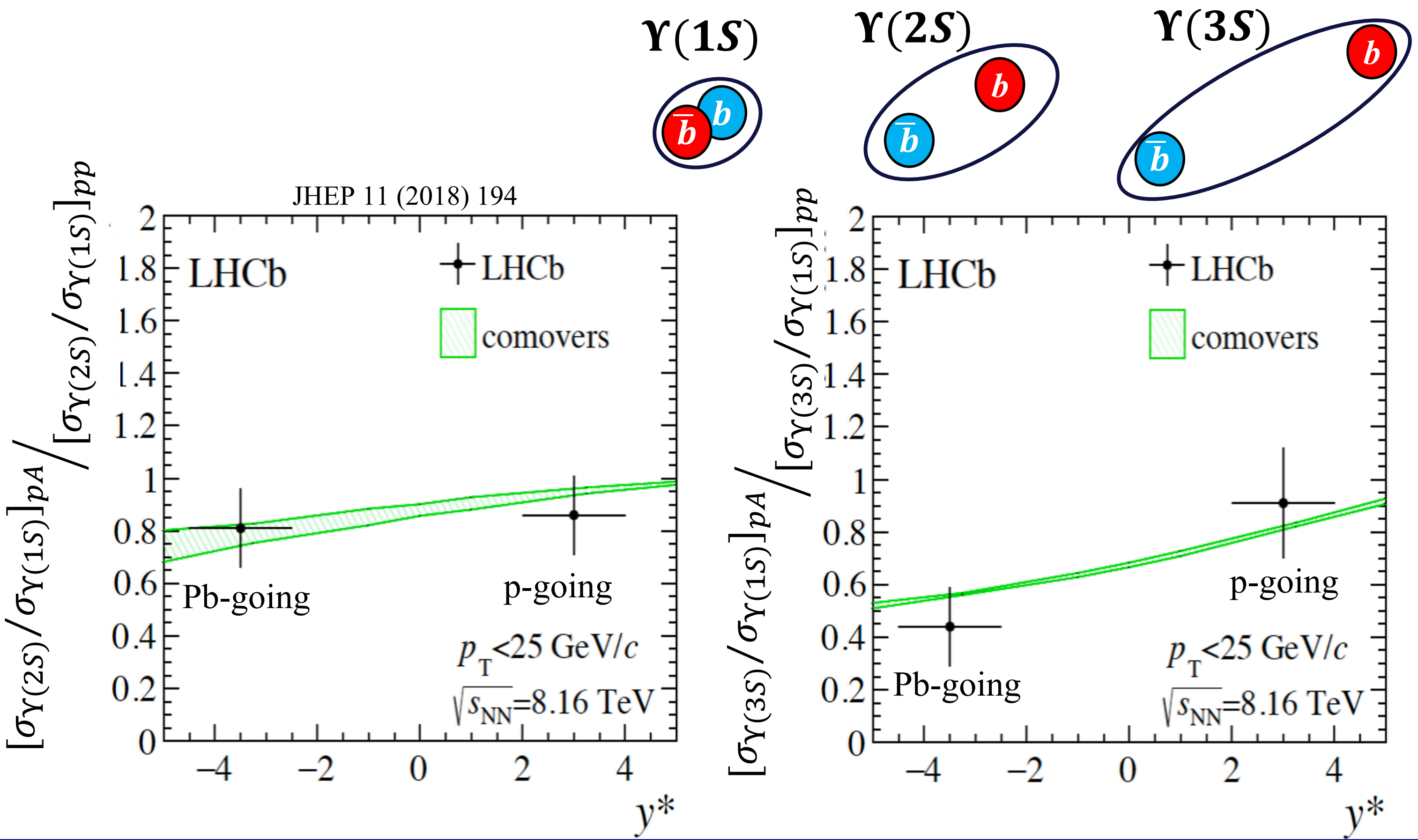

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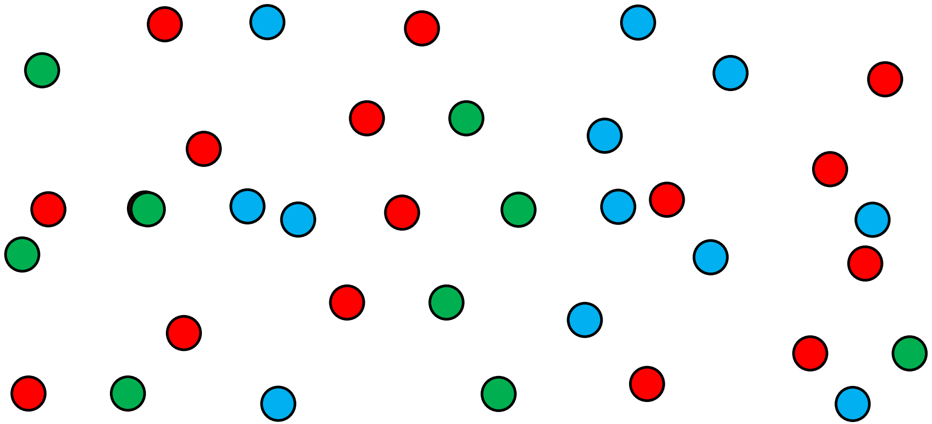

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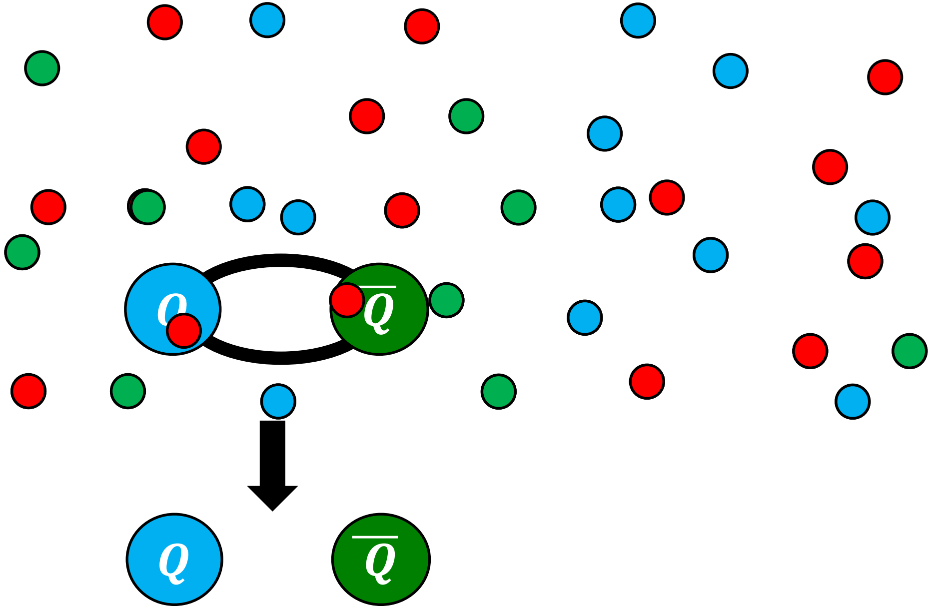

Comover breakup:

- Weakly bound states interact with other produced particles and are disrupted preferentially more than tightly bound states

Phys. Lett. B, 393(3):431, (1997)
Phys. Rev. Lett., 78:1006–1009 (1997)
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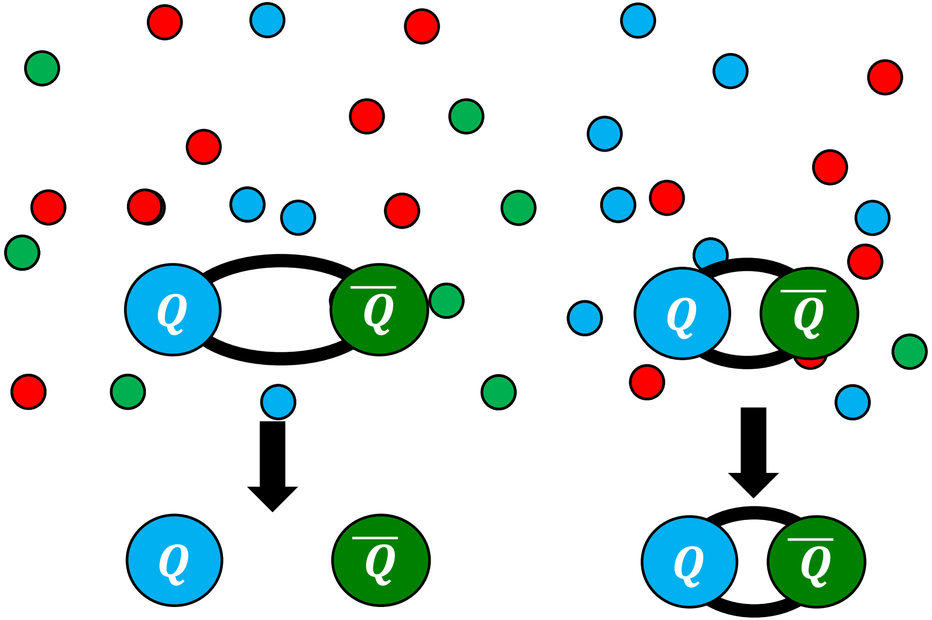

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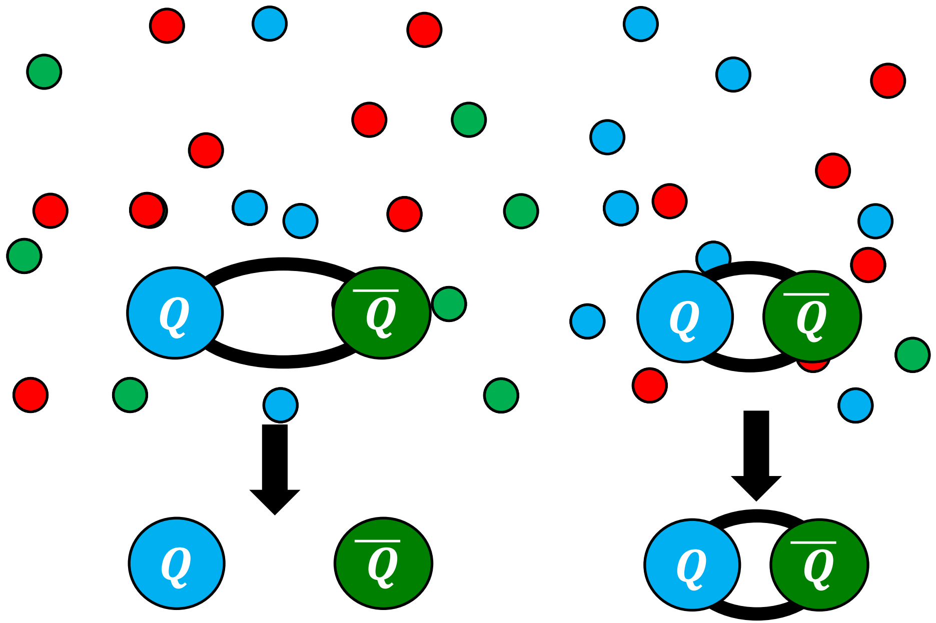
JHEP, 2018(10):94 (2018)

Quarkonia in the QCD medium



Comover breakup:

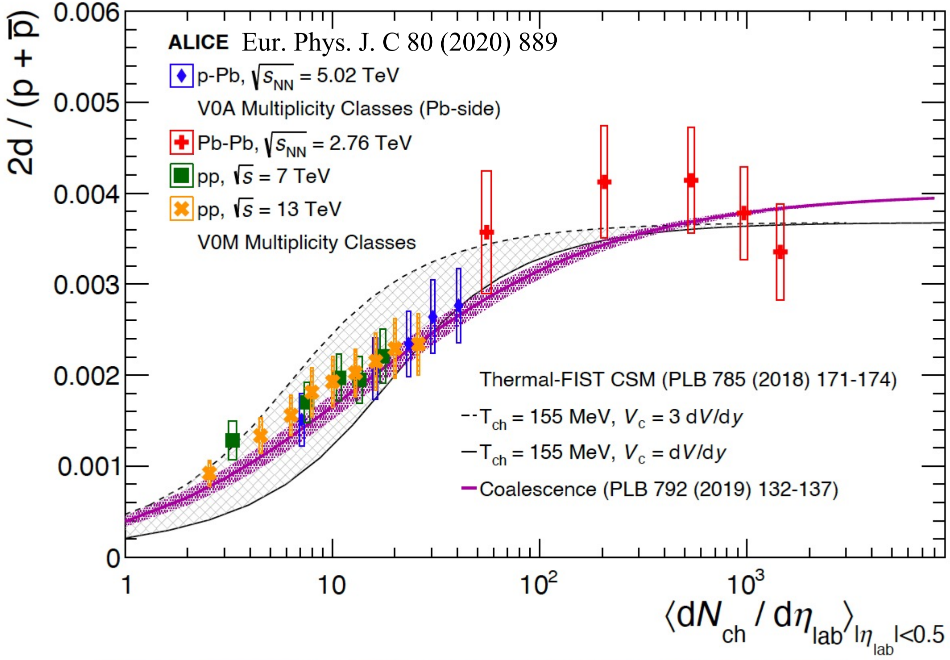
- Weakly bound states interact with other produced particles and are disrupted preferentially more than tightly bound states

Phys. Lett. B, 393(3):431, (1997)
Phys. Rev. Lett., 78:1006–1009 (1997)
Phys. Lett. B, 749:98, (2015)
Phys. Rev. C, 97:014909 (2018)
JHEP, 2018(10):94 (2018)

Effect is sensitive to ***size of bound state*** and ***density of medium***

Deuteron production in the QCD medium

Deuteron: weakly bound state of neutron and proton, $E_b \approx 2\ MeV$



Diffuse medium (pp,pA) Increasing T, $N_{charged}$ Dense medium (pA, AA)

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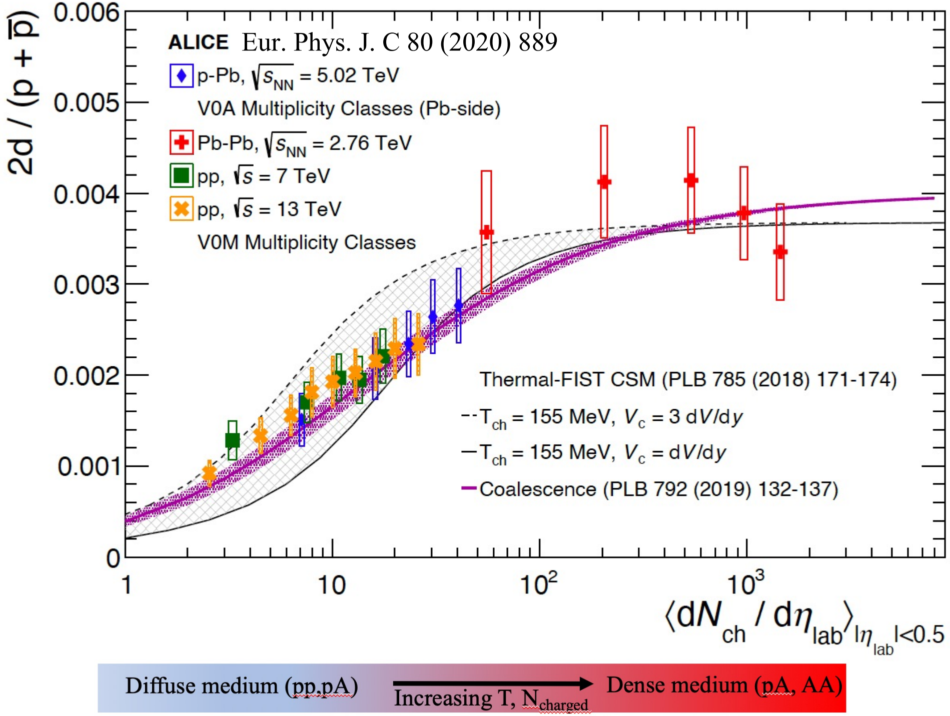
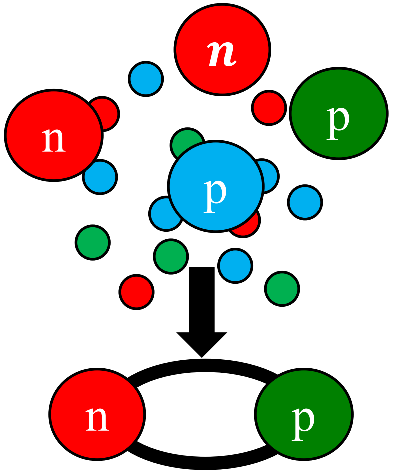


Production relative to protons increases with system density:



Well described by coalescence models.

Outline

- Conventional quarkonium - $Q\bar{Q}$ bound states
  - Simple quantum mechanical system
  - Interactions with a hadronic medium
- Exotic quarkonium - multiquark states
  - Few examples
  - Detailed look at X(3872) and T_{cc}^{+} in medium
- Outlook: future measurements
  - Fixed-target collisions at the LHC
  - Electron-Ion Collider

We have identified effects that depend on binding energy/radius of state and QCD medium properties

Outline

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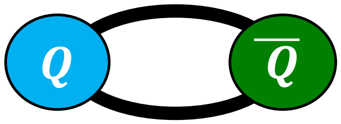
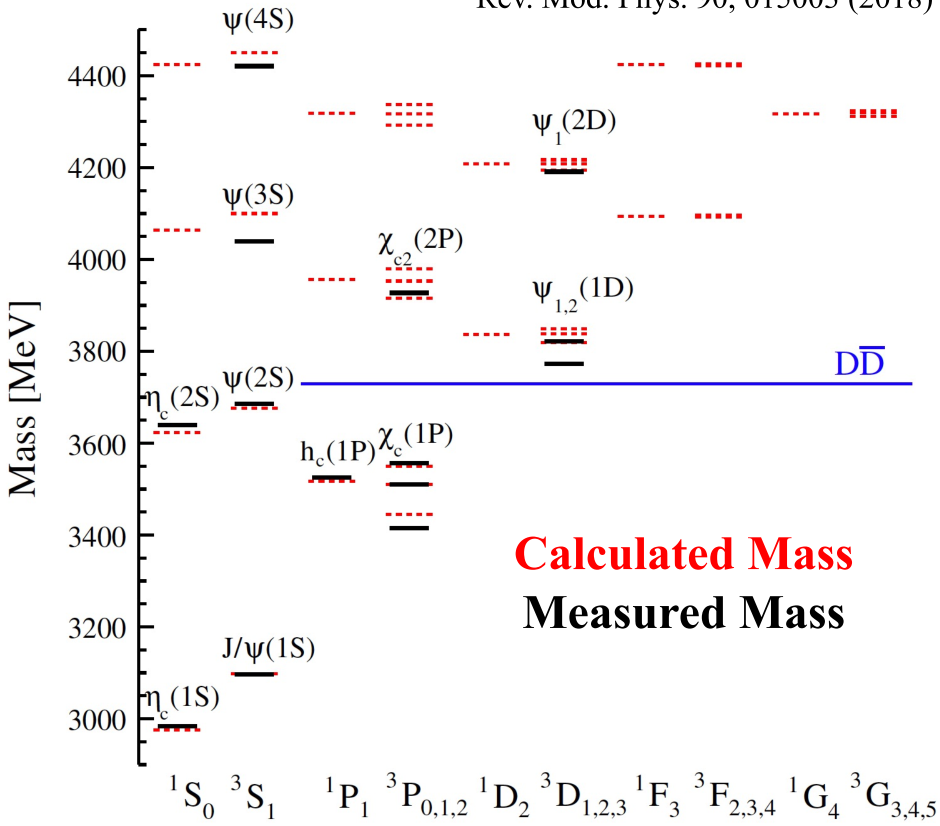
Exotic hadrons



Rev. Mod. Phys. 90, 015003 (2018)



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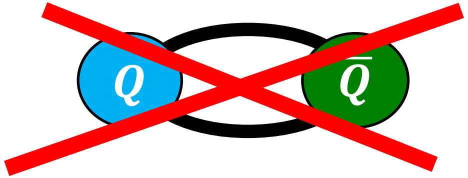
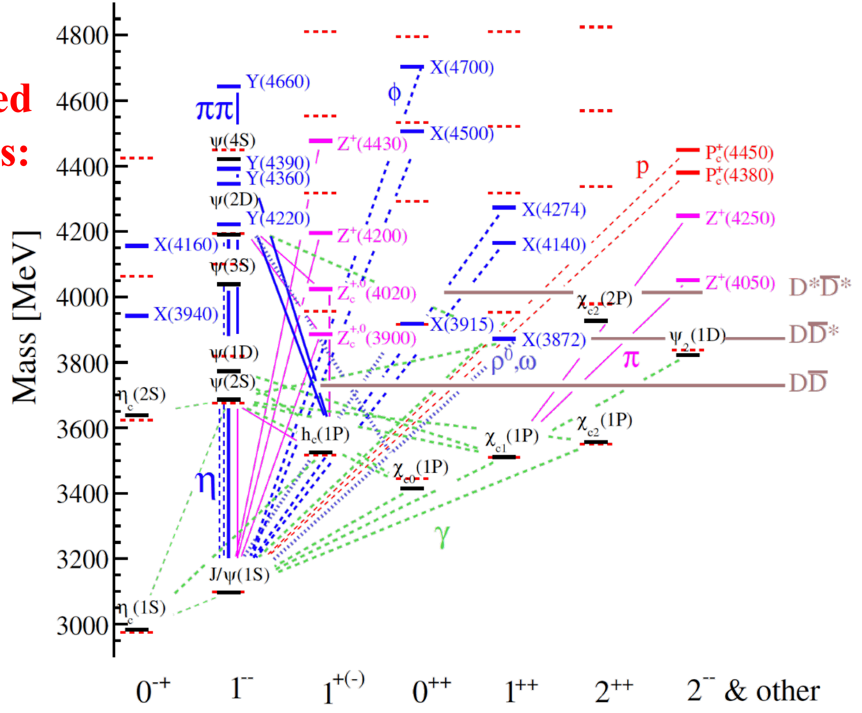


20+ states containing heavy quarks have been discovered since 2003 that do not fit typical quarkonium properties: Collectively known as "*XYZ*" particles

Rev. Mod. Phys. 90, 015003 (2018)



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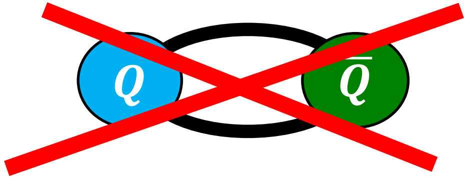

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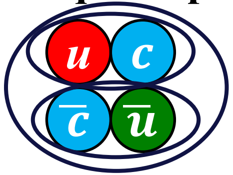
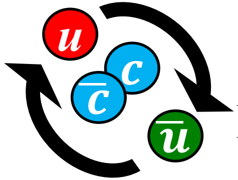
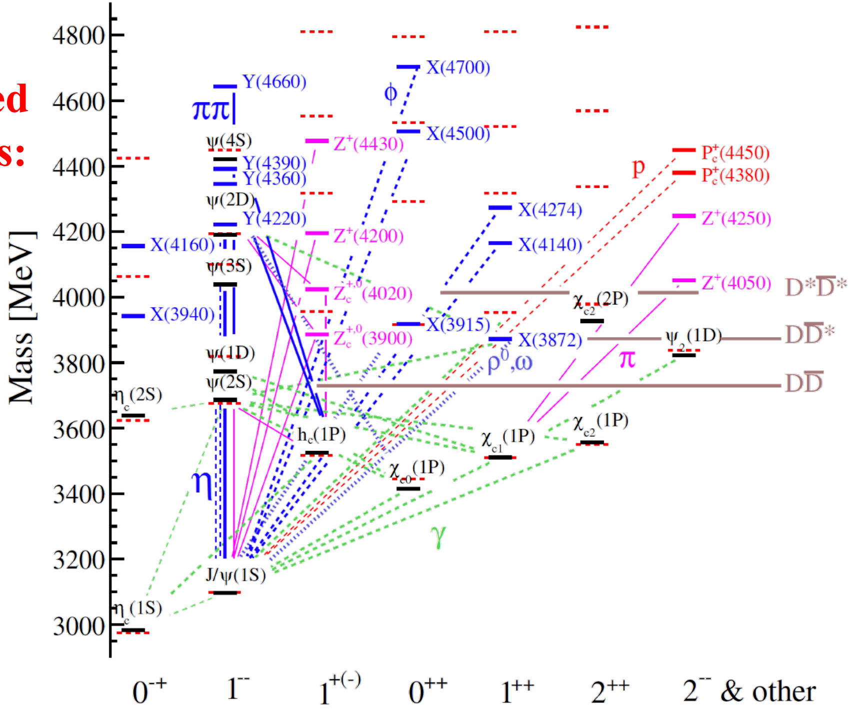


Diquark-diquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Rev. Mod. Phys. 90, 015003 (2018)



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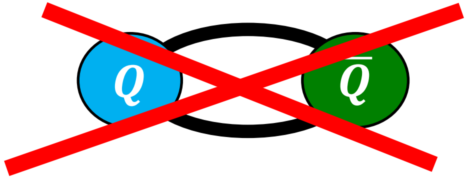

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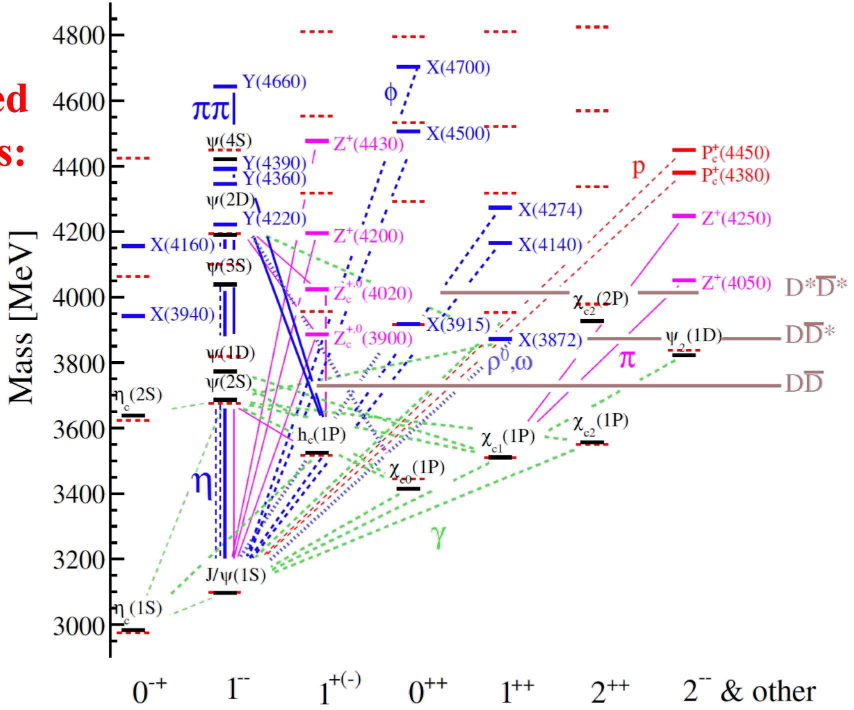

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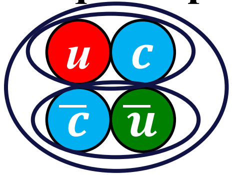

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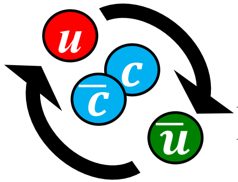

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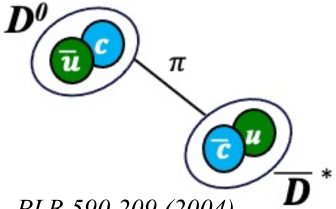
Hadronic Molecule



PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

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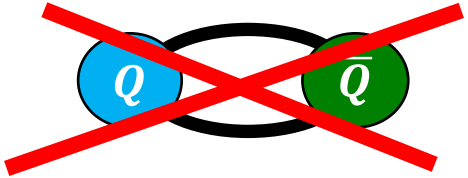

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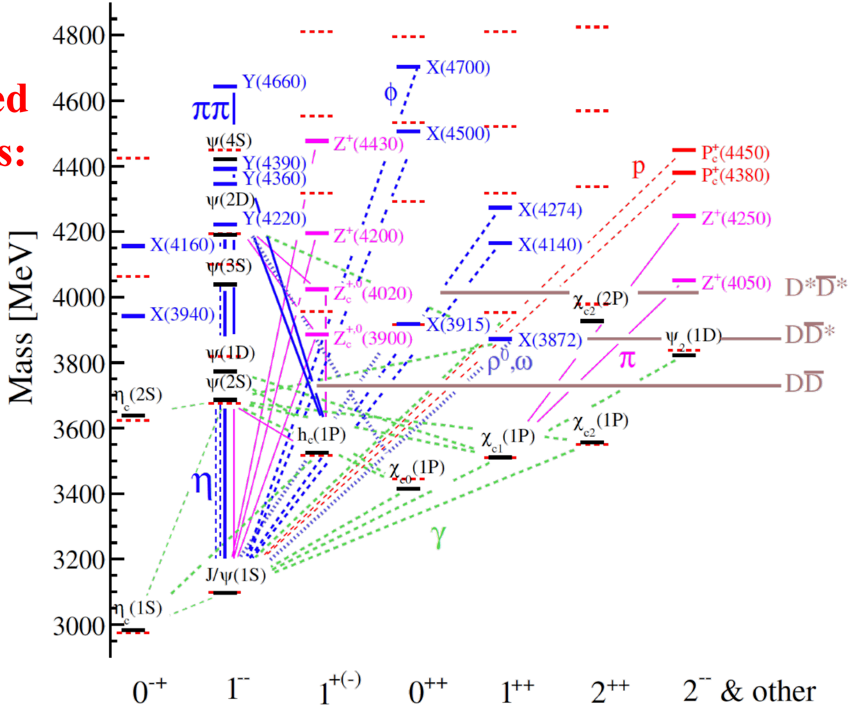

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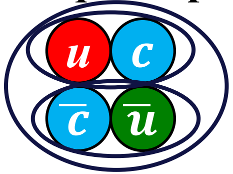

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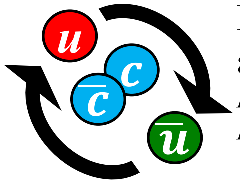

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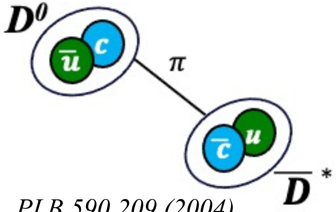

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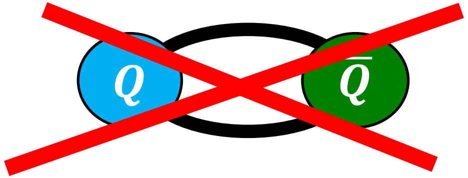
Mixtures of exotic + conventional states

$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

Exotic hadrons



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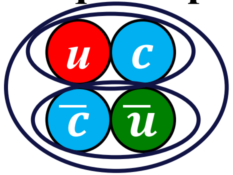

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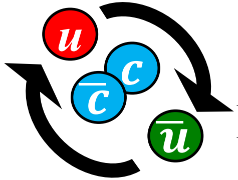

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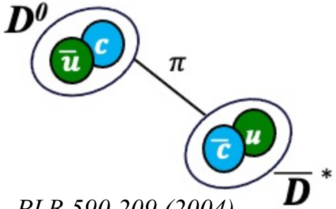

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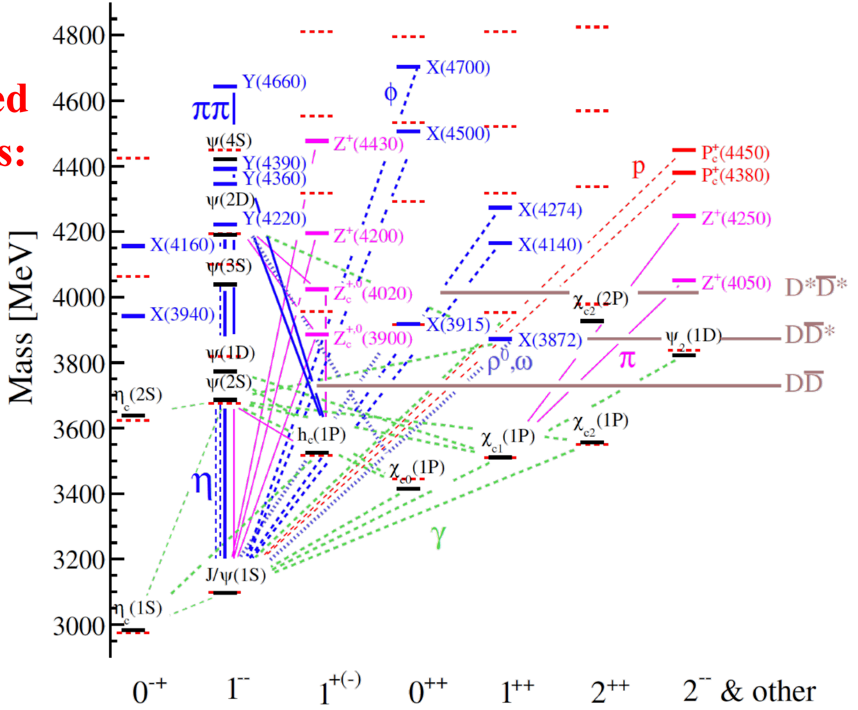

Multiple structures likely necessary to fully describe all states and their properties

Example: $P_c^{\pm}$ pentaquarks

Select daughters from the decay

$$\Lambda_b^0 \to J/\psi p K^-$$

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PRL 122 222001 (2019)

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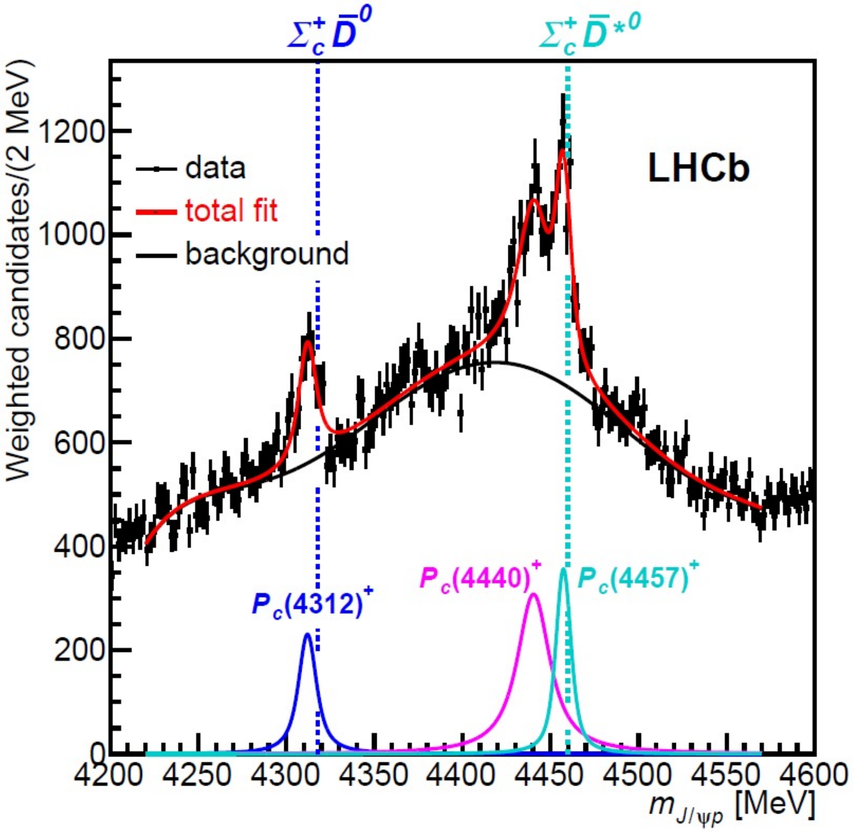

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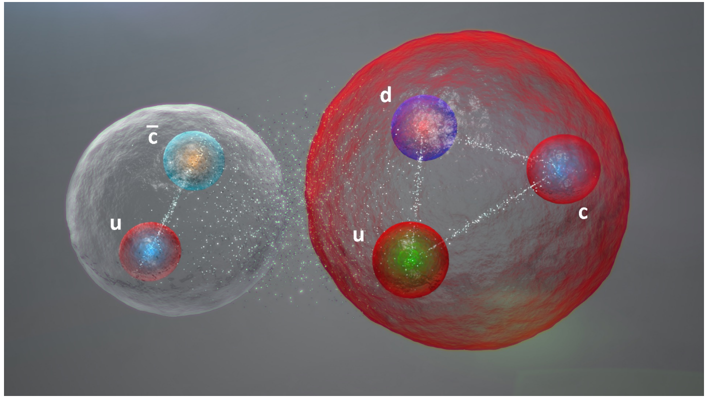
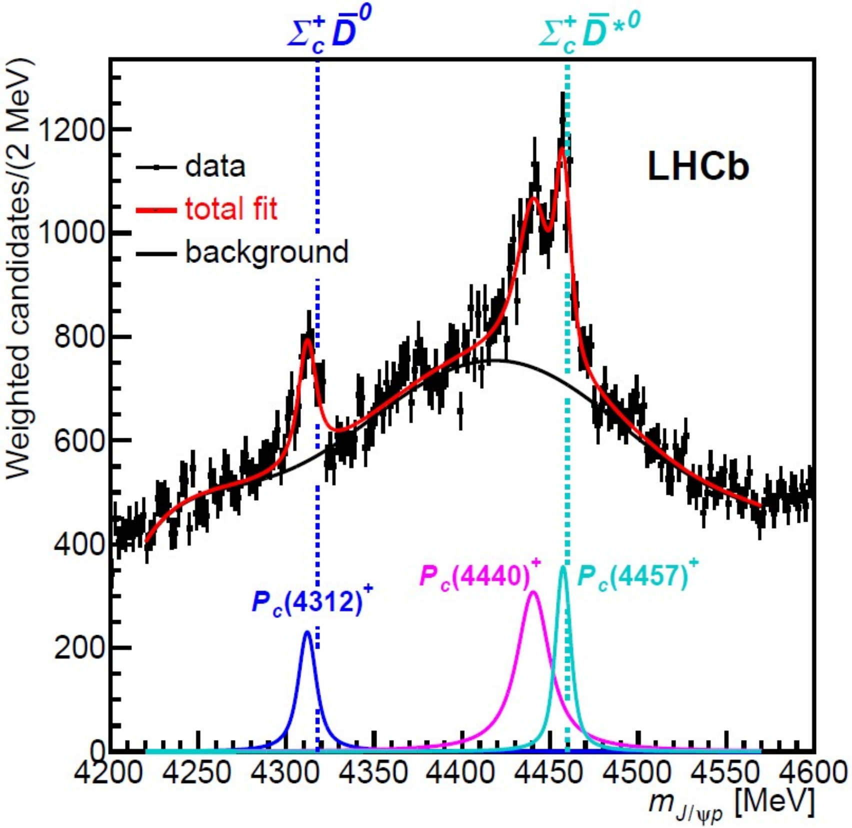
Masses are close to meson+baryon thresholds – candidate hadronic molecule



PRL 122 222001 (2019)



Example: Charged Tetraquark: $Z_c^{\pm}$

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$$B^0 \rightarrow \psi(2S)K^+\pi^-$$

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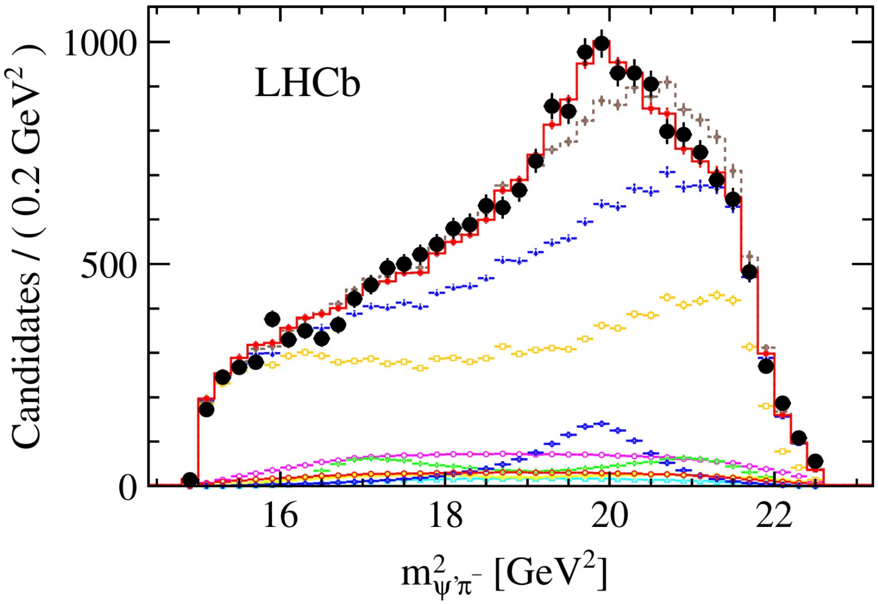
PRL 112 222002 (2014)



Example: Charged Tetraquark: $Z_c^{\pm}$

Select daughters from the decay

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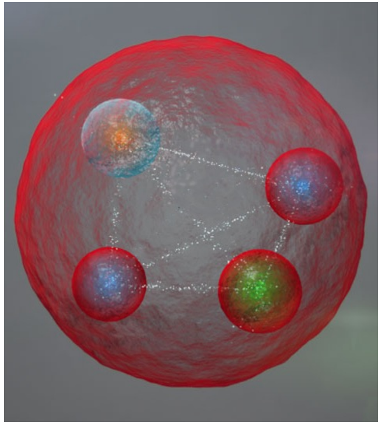
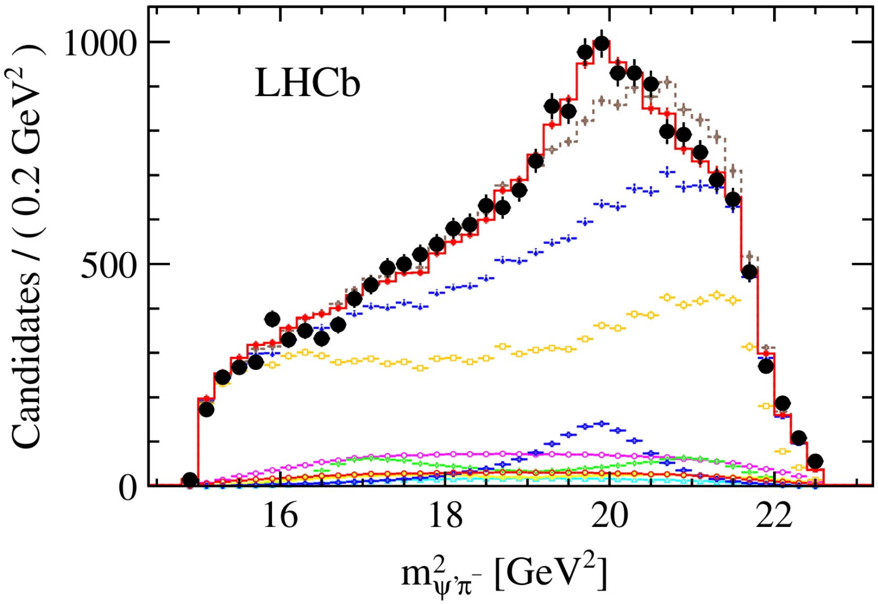
Charged and contains $c\bar{c}$ pair:
minimal quark content $c\bar{c}q\bar{q}$

Mass not close to hadron+hadron threshold – candidate compact tetraquark

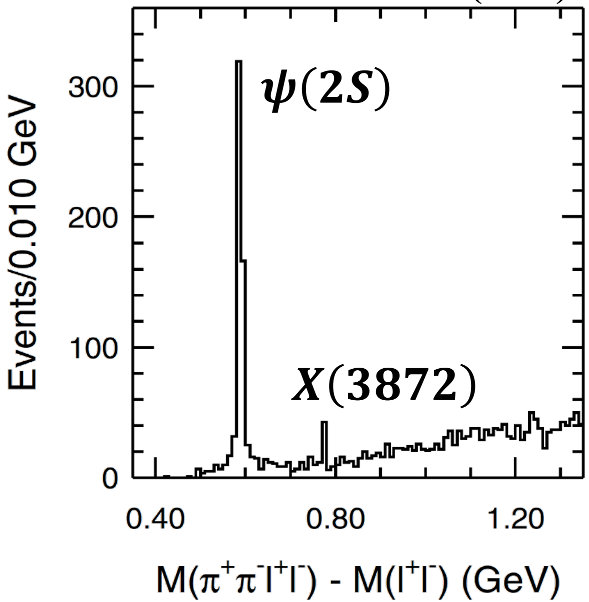


PRL 112 222002 (2014)



An enduring puzzle: X(3872)

Belle Collaboration
PRL 91 262001 (2003)



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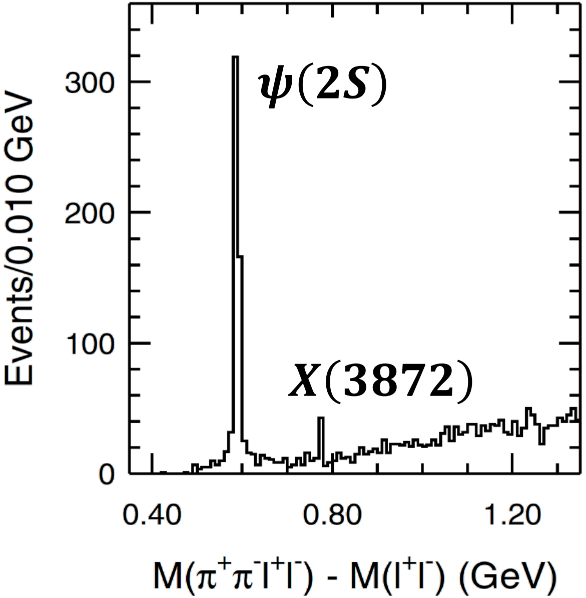

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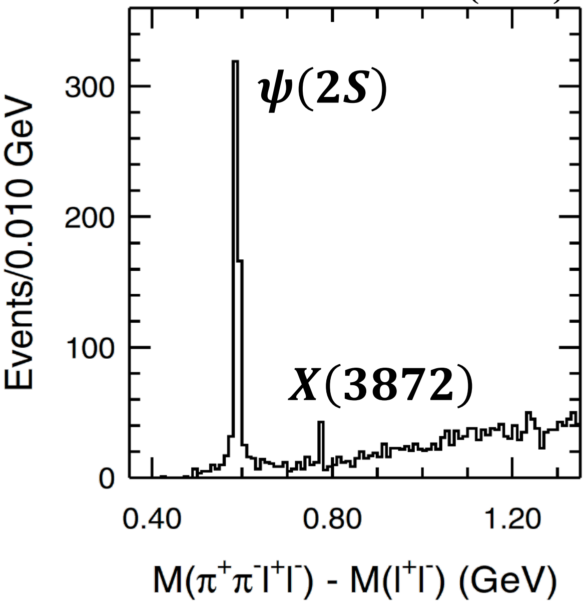

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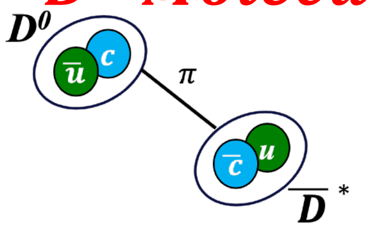
- Mass is consistent with sum of D^0 and $\overline{D}^{*0}$ masses:

$$\left(M_{D^0} + M_{\bar{D}^{*0}}\right) - M_{\chi_{c1}(3872)} = 0.07 \pm 0.12\ \mathrm{MeV}/c^2$$

$D^0\overline{D}^*$ Molecule



VERY **small binding energy**
VERY **large radius, ~10 fm**

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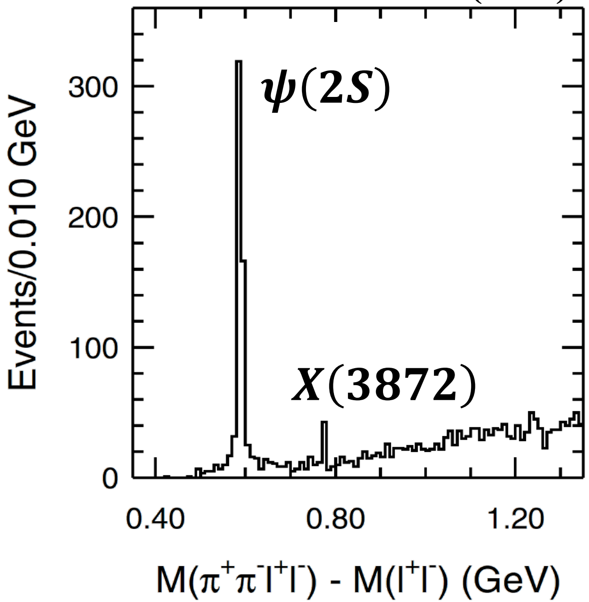

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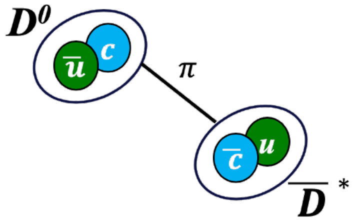
- Large prompt production fraction (~80%) – inconsistent with D meson coalescence in pp*

$D^0\bar{D}^*$ Molecule



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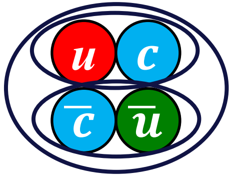


Tightly bound via color exchange between diquarks
Small **radius, ~1 fm**

*Tension in theoretical literature:
c.f. Bignamini, Grinstein et al
PRL 103 162001 (2009)
Artoisenet, Braaten
PRD 81 114018 (2010)

Probing exotic structure with comovers at LHCb

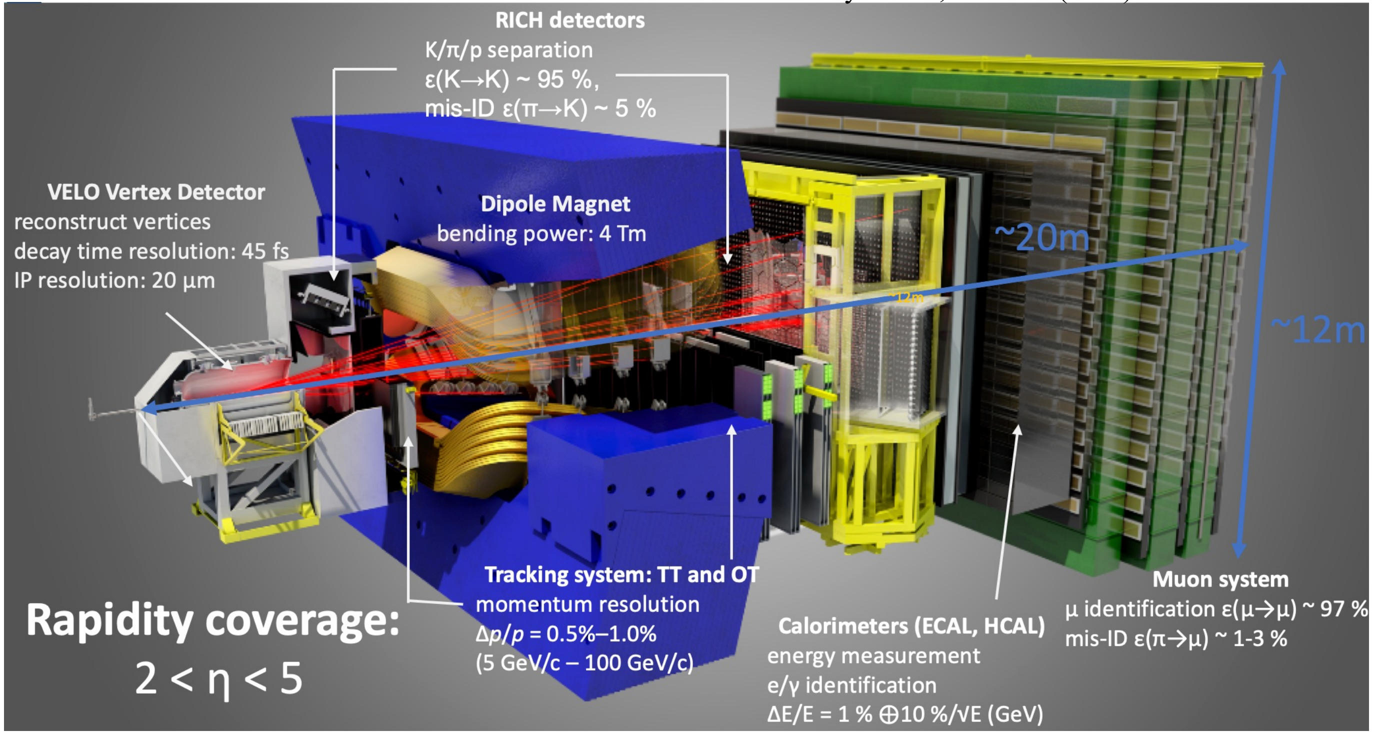
JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)

$$X(3872) \to J/\psi\pi^+\pi^-$$

Vertex detector (VELO):
-Separation of prompt and ***b***-decay production
-Number of VELO tracks gives measure of event activity

Two RICH detectors:
-Pion identification

Muon System:
-Layers of absorber/tracking
-Muon hardware trigger

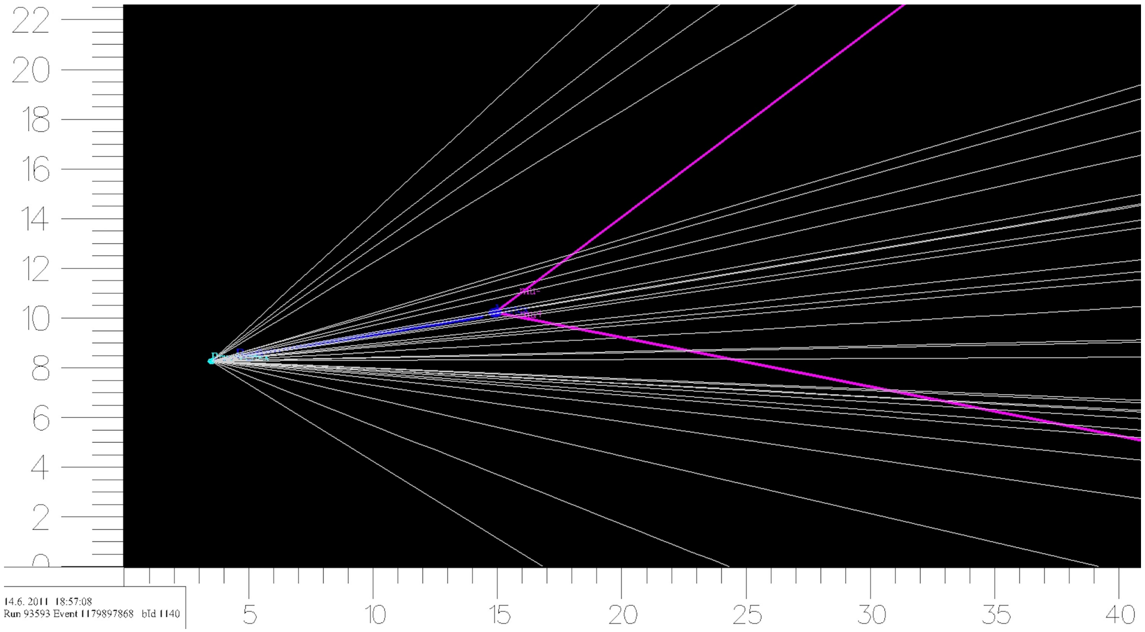


Probing exotic structure with comovers at LHCb

Prompt production:
- X(3872) produced at collision vertex can be subject to further interactions with co-moving particles produced in the event
- Potentially subject to breakup effects

Production in ***b***-decays:
- Hadrons containing ***b*** travel down the beampipe and decay away from the primary vertex and decay in vacuum
- X(3872) from decays not subject to further interactions
- Control sample

Event display of $\boldsymbol{B_s^0} \rightarrow \boldsymbol{\mu^+\mu^-}$ candidate



X(3872) measurement at LHCb

Reconstruct the $\mu^+\mu^-\ \pi^+\pi^-$ final state from the decays:

$$X(3872) \to J/\psi(\to \mu^+\mu^-)\rho(\to \pi^+\pi^-)$$

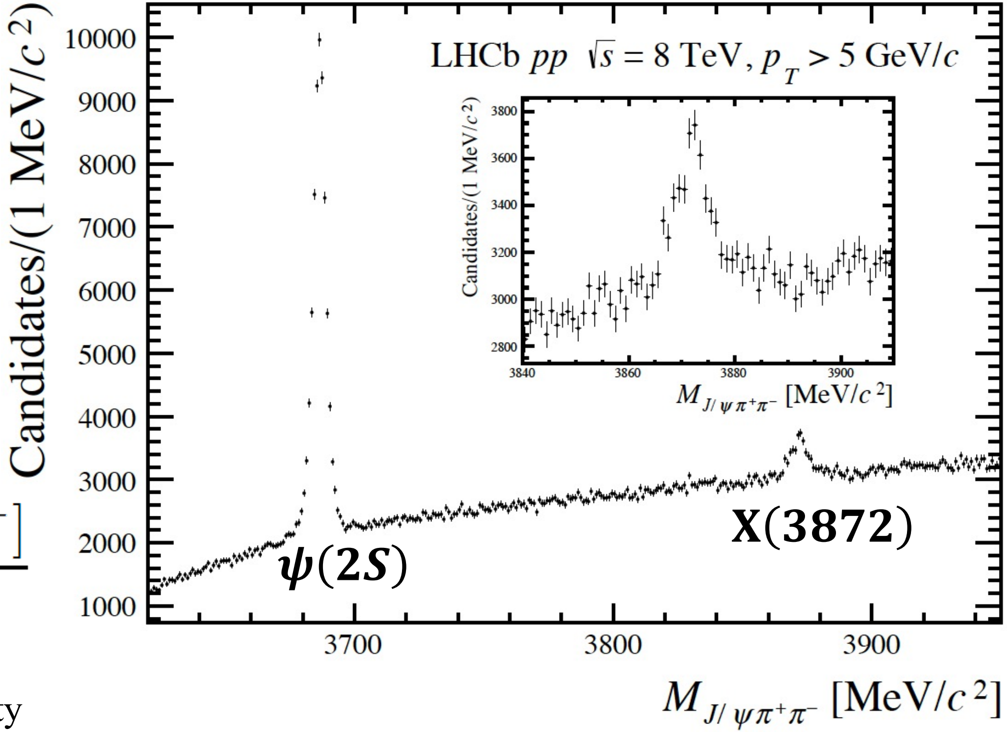
$$\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$$

Direct comparison between conventional charmonium $\psi(2S)$ and exotic $X(3872)$ via ratio of cross sections:

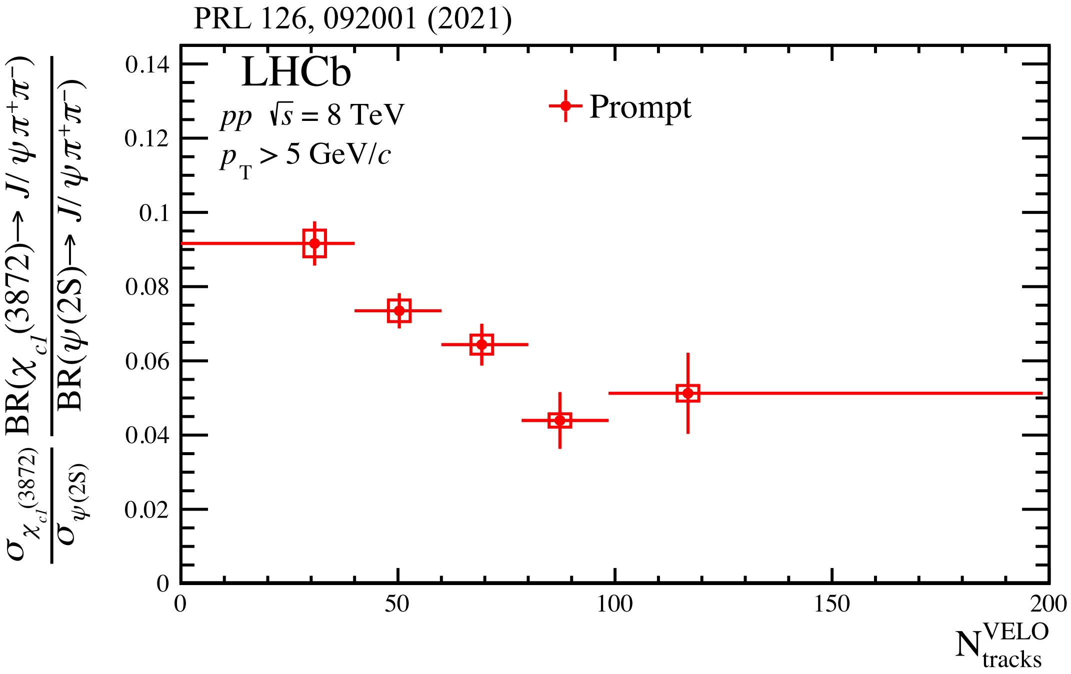
$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-]}{\mathcal{B}[\psi(2S) \to J/\psi\,\pi^+\pi^-]}$$

Select collisions of various charged particle multiplicity to vary density of comoving medium

PRL 126, 092001 (2021)

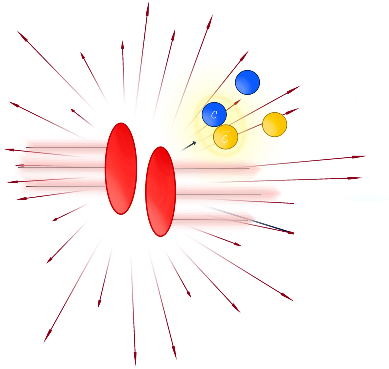


X(3872)/ψ(2S) vs multiplicity



Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases



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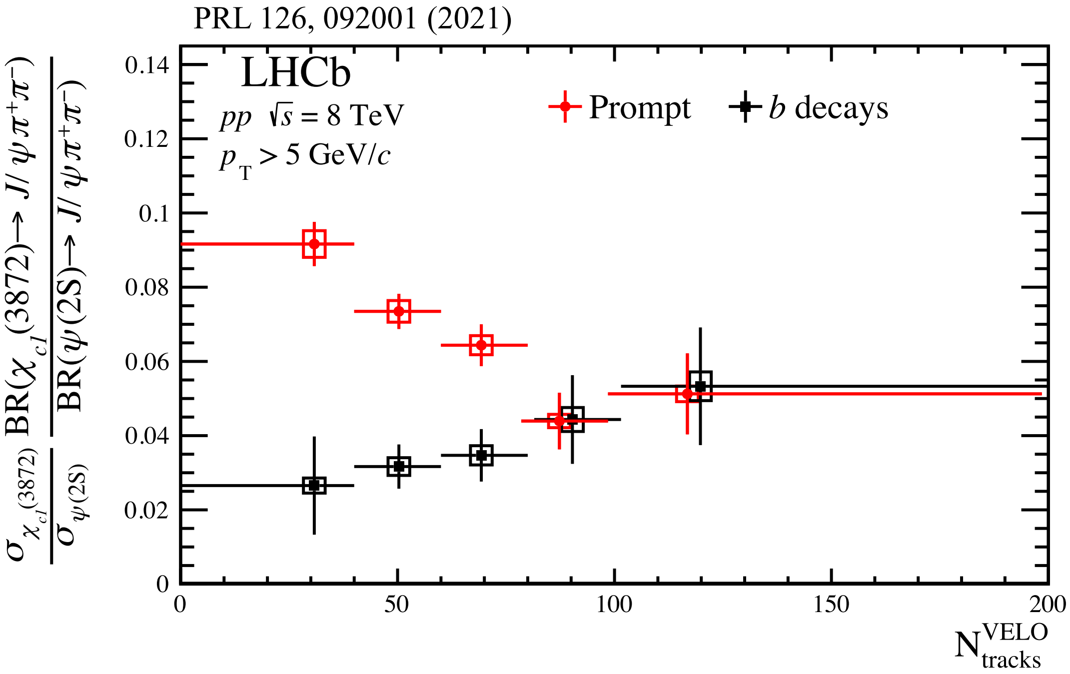

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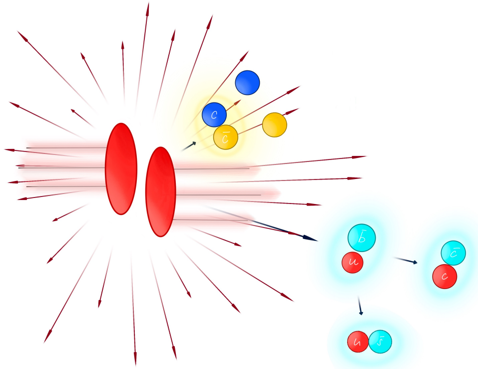
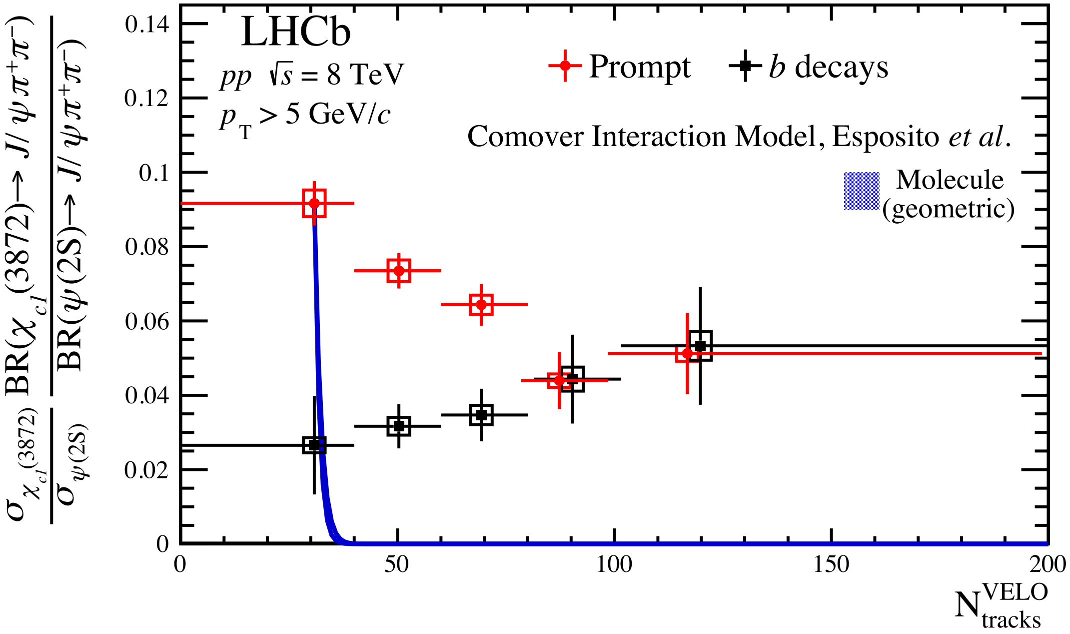
***b*-decay component:**

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.



X(3872)/ψ(2S)

PRL 126, 092001 (2021)



Molecular X(3872) with large radius and large comover breakup cross section is immediately dissociated

Prompt component:

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Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.

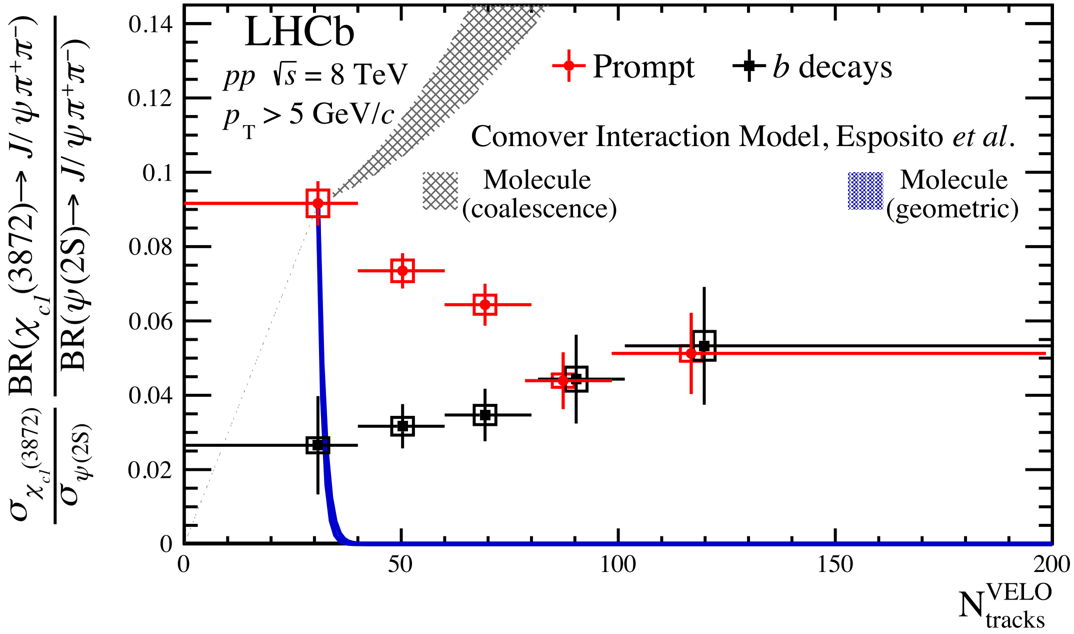
Calculations from EPJ C 81, 669 (2021)

Break-up cross section:

$$\langle v\sigma \rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\text{geo}} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{\text{thr}}}{E_c}\right)^n \right\rangle$$

X(3872)/ψ(2S)

PRL 126, 092001 (2021)



Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

***b*-decay component:**

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.

Calculations from EPJ C 81, 669 (2021)

Break-up cross section:

$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\text{geo}} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{\text{thr}}}{E_c}\right)^n \right\rangle$$

Molecular X(3872) with large radius and large comover breakup cross section is immediately dissociated

Coalescence of D mesons into molecular X(3872) increases ratio

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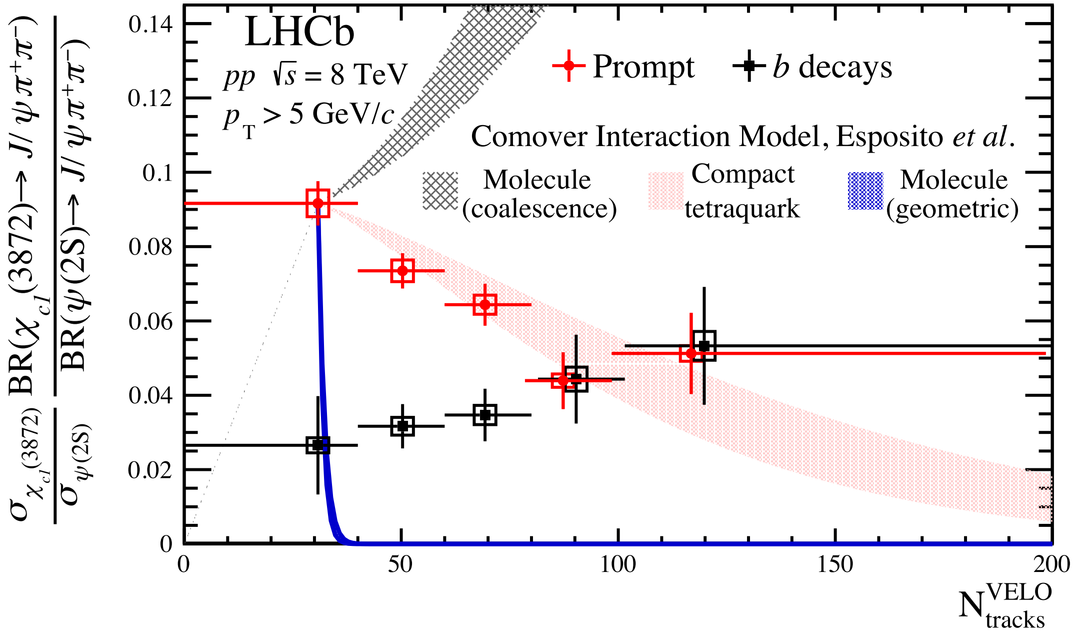

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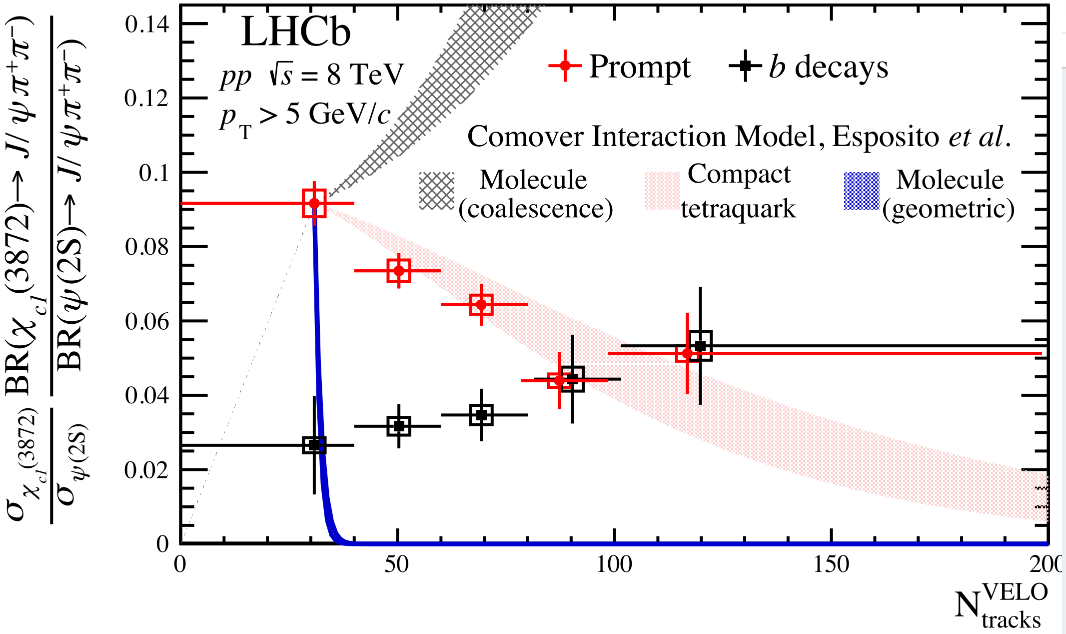
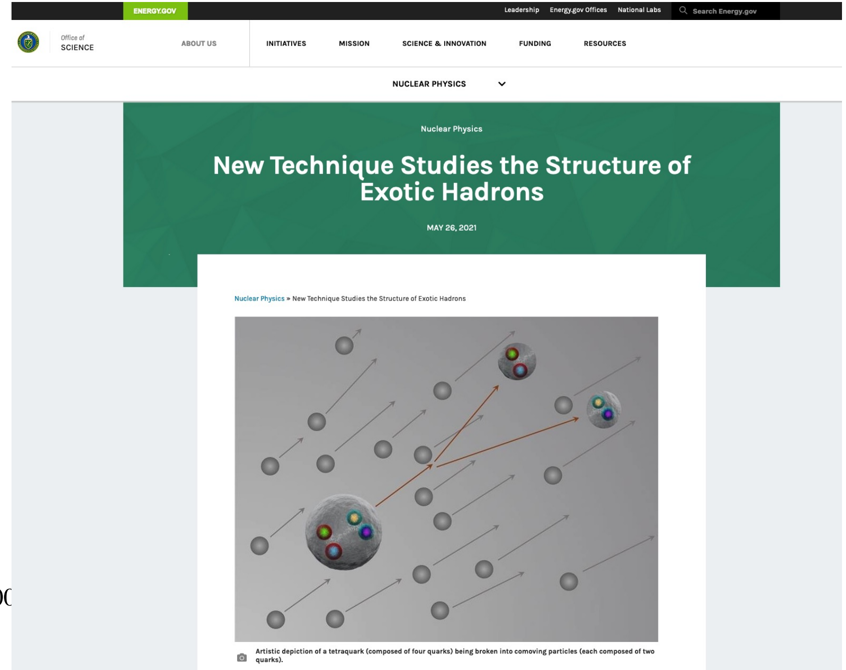
X(3872)/ψ(2S)

DOE NP highlight

PRL 126, 092001 (2021)





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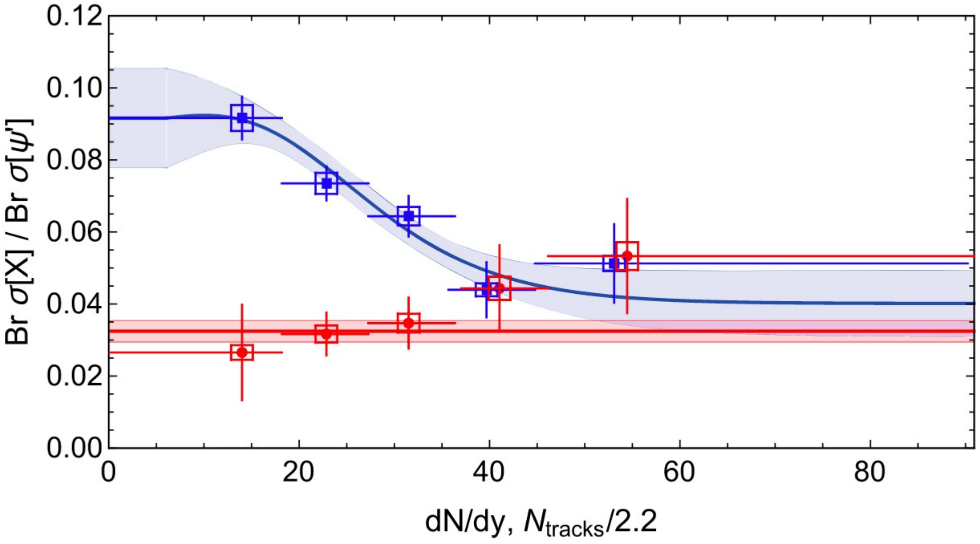
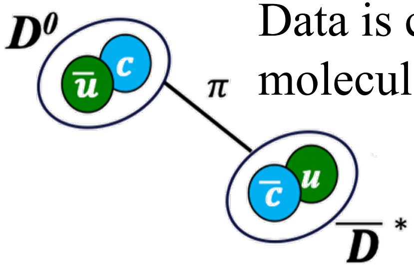
Comover model: constituent interaction

Different method of calculating breakup cross section:
Braaten, He Ingles, Jiang Phys. Rev. D 103, 071901 (2021)



Breakup cross section approximated as sum of cross section for molecule constituents:

$$\sigma^{\mathrm{incl}}[\pi X] \approx \frac{1}{2}\left(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}]\right)$$



Data is consistent with this molecular interpretation.

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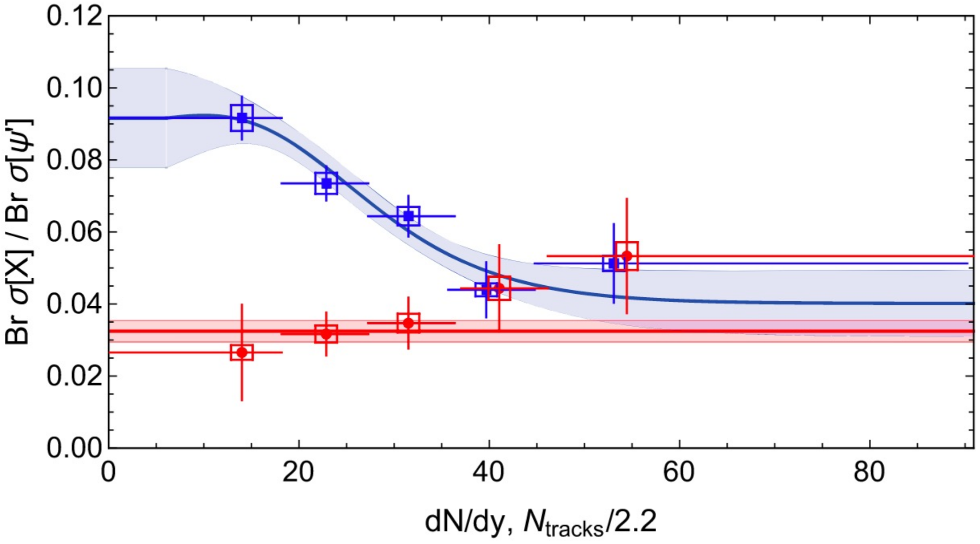

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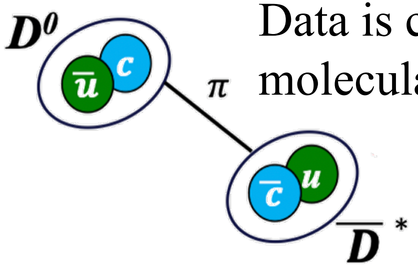
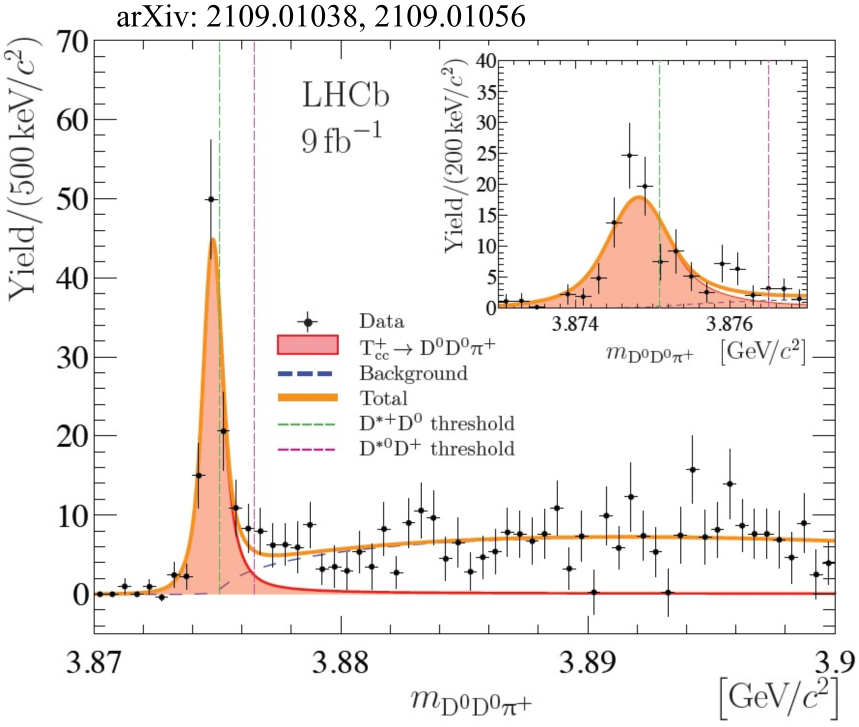


Data is consistent with this molecular interpretation.

If breakup is due to scattering of individual constituents, would all $c\bar{c}$ have equal suppression? Not observed in charmonium or bottomonium systems.

Newest LHCb exotic: T_{cc}^{+}



New state consistent with $cc\bar{u}\bar{d}$ tetraquark recently found:

Similar to X(3872), mass quite close to DD threshold

Big difference: contains cc or $\bar{c}\bar{c}$, rather than $c\bar{c}$

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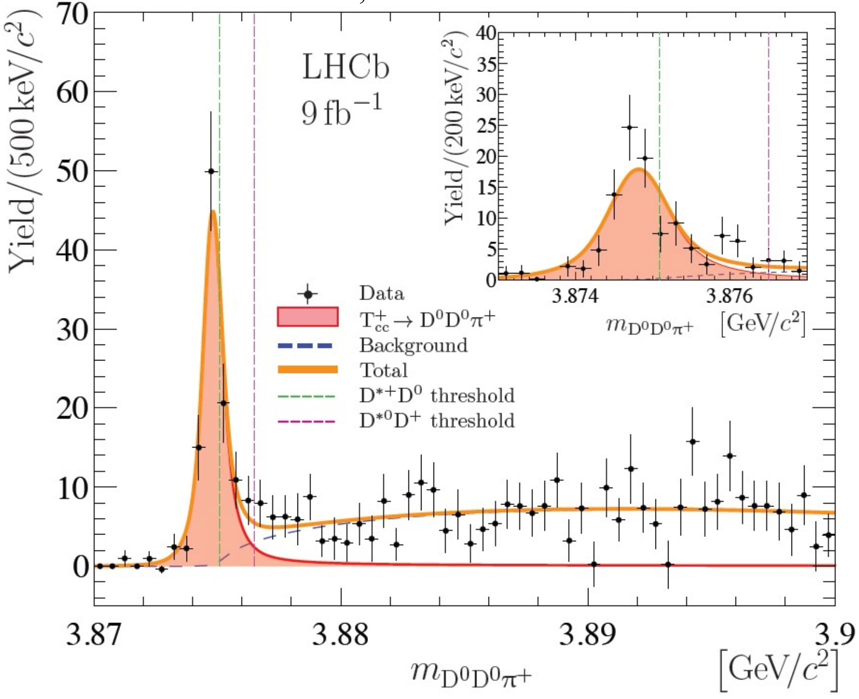
arXiv: 2109.01038, 2109.01056



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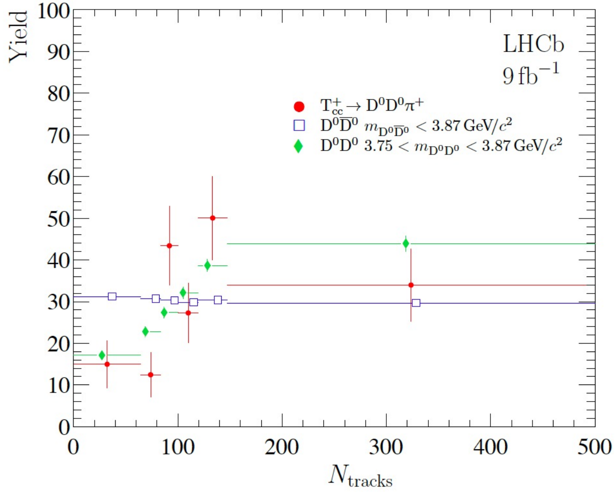
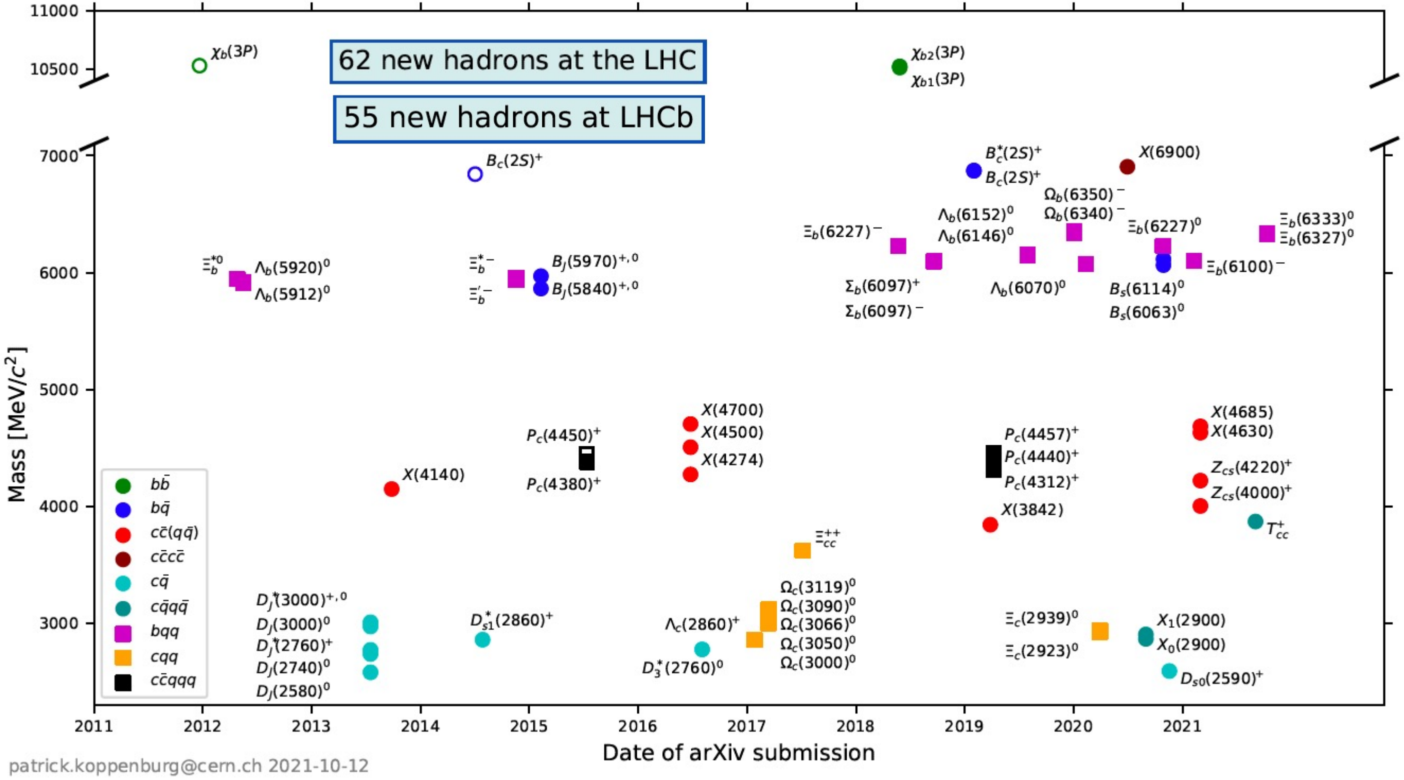


Yield favors higher multiplicity collisions, reminiscent of deuteron.

Evidence for hadronic molecule structure?

New Particles at the LHC



https://www.nikhef.nl/~pkoppenb/particles.html

Outline

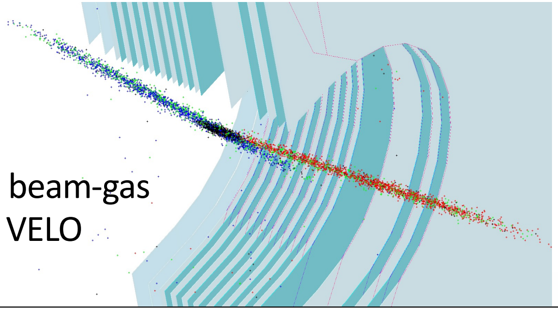
- Conventional quarkonium - $Q\bar{Q}$ bound states
  - Simple quantum mechanical system
  - Interactions with a hadronic medium

- Exotic quarkonium - multiquark states
  - Few examples
  - Detailed look at X(3872) and T_{cc}^{+} in medium

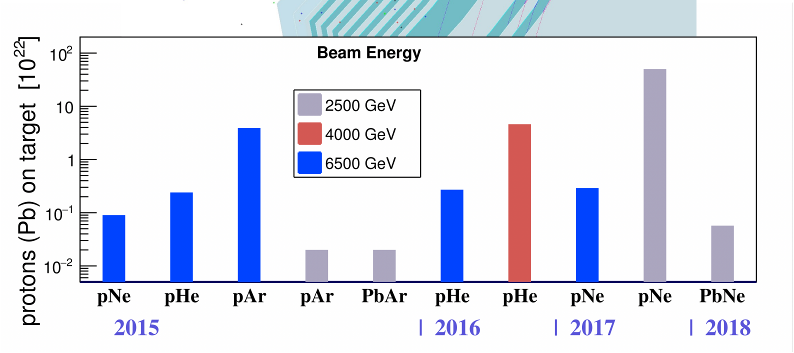
- Outlook: future measurements
  - Fixed-target collisions at the LHC
  - Electron-Ion Collider

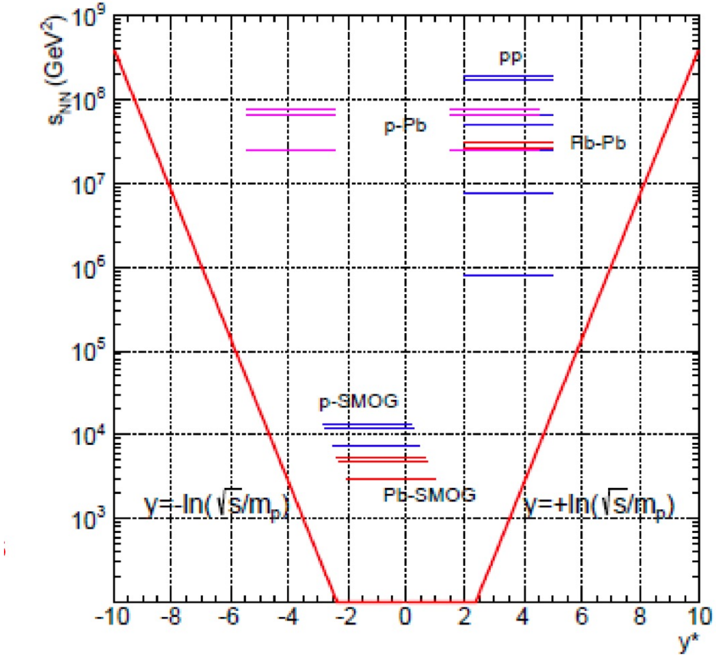
Fixed target configuration - SMOG

System for **M**easurement of **O**verlap with **G**as
A unique capability at LHCb: inject noble gas into beampipe
Originally intended for precise luminosity measurements:
Precision on 2012 pp data is ±1.16%, best ever at bunched beam collider
JINST **9** P12005 (2014)



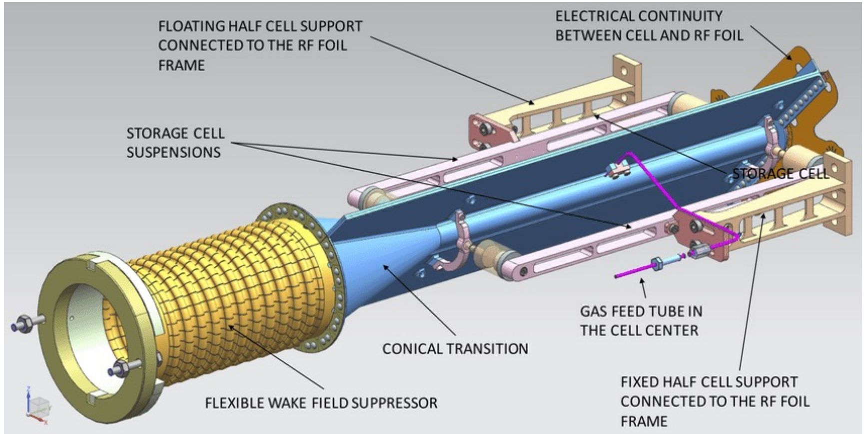
Reconstructed beam-gas vertices inside VELO





Measurements so far:
Charm production in p+He and p+Ar: PRL 122 132002 (2019)
Antiproton production in p+He: PRL 121 222001 (2018)

Near future: SMOG II at LHCb



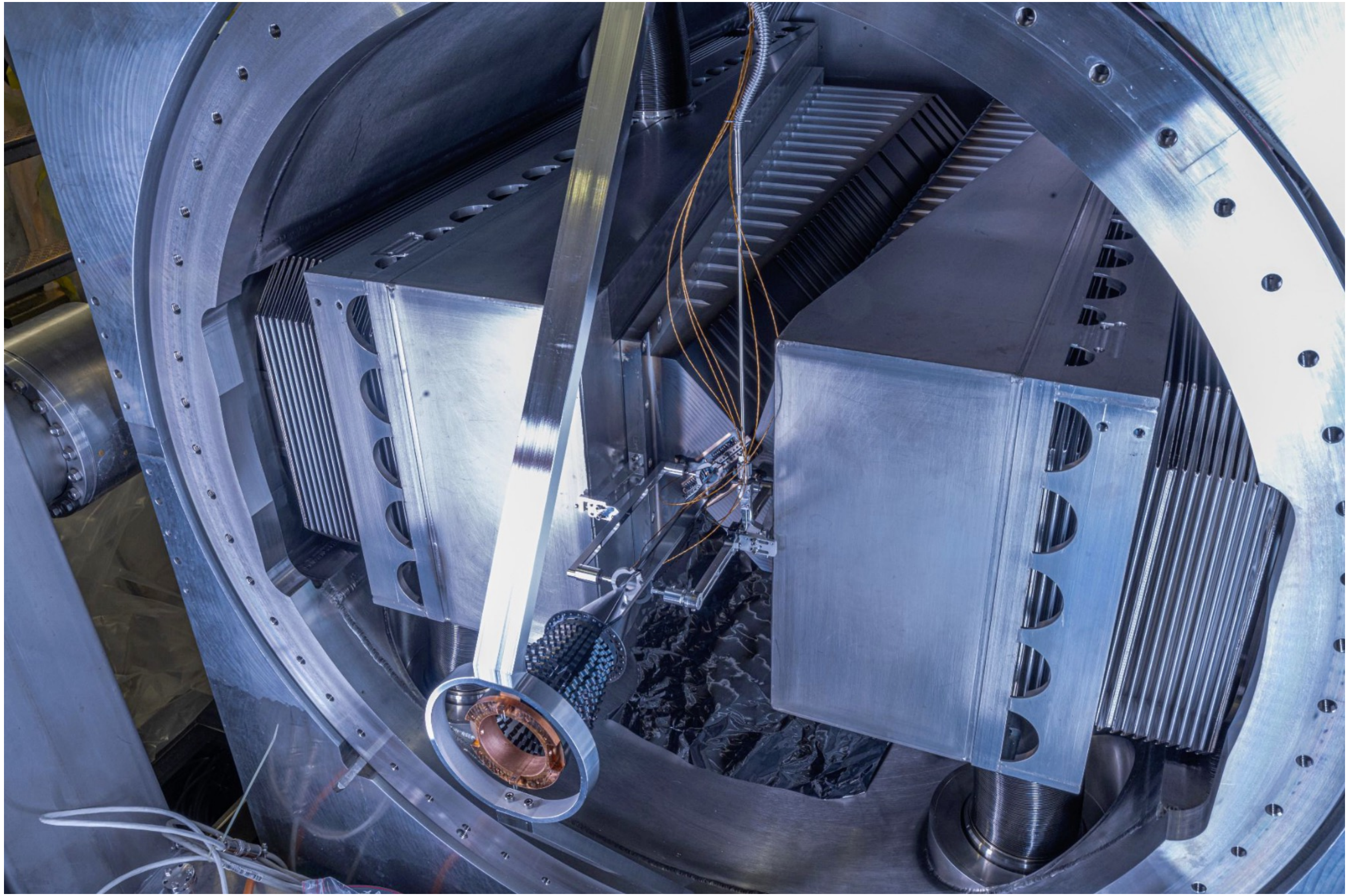
https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf

Example SMOG2 pAr at 115 GeV for one year

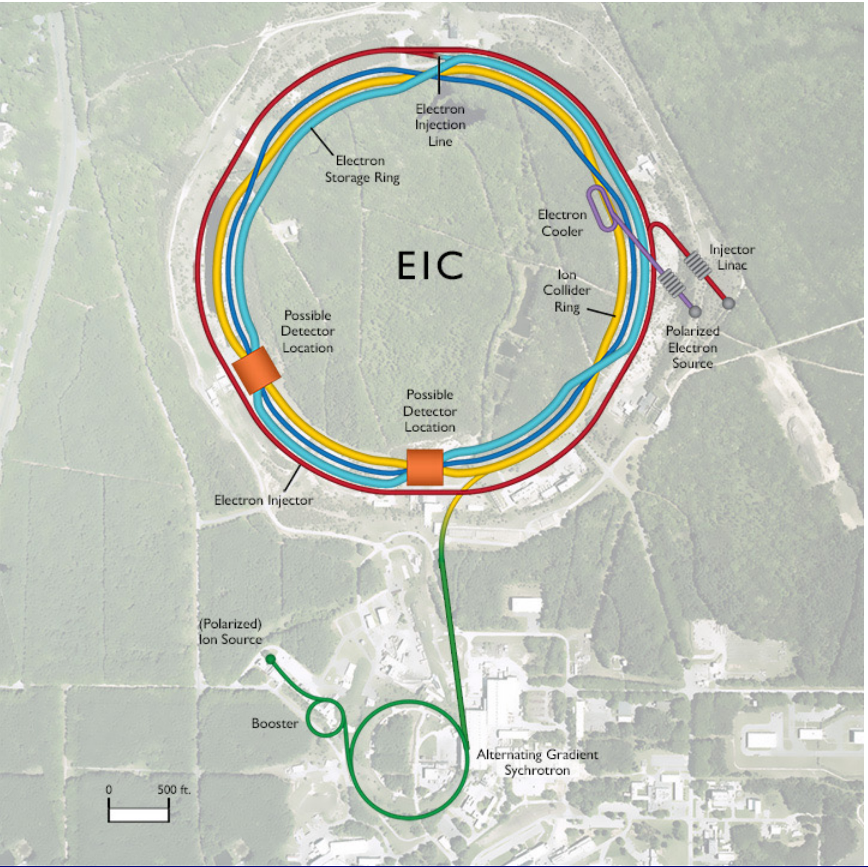
Int. Lumi.		80 pb^{-1}
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

- Upgraded SMOG 2 system at LHCb allows greatly increased rates of beam+gas collisions at LHCb
- Variable target gases – allows hadronic environment to be adjusted (H, He, …, Xe)
- Access to exotic states near RHIC energies
- Can potentially run concurrent with proton+proton collisions – large data sets

SMOG II installed at LHCb



Future facility: Electron-Ion Collider



EIC site selection at BNL announced Jan 2020, CD-1 July 2021, operational ~2030

$$\sqrt{s} \sim 20 - 100\ GeV$$

e+p, *e+*O, *e+*Al, *e+*Cu, *e+*Au, *e+*U,…

Charm production inside the nucleus probes:

- Parton structure of nucleons
- Parton distribution function modifications
- QCD energy loss

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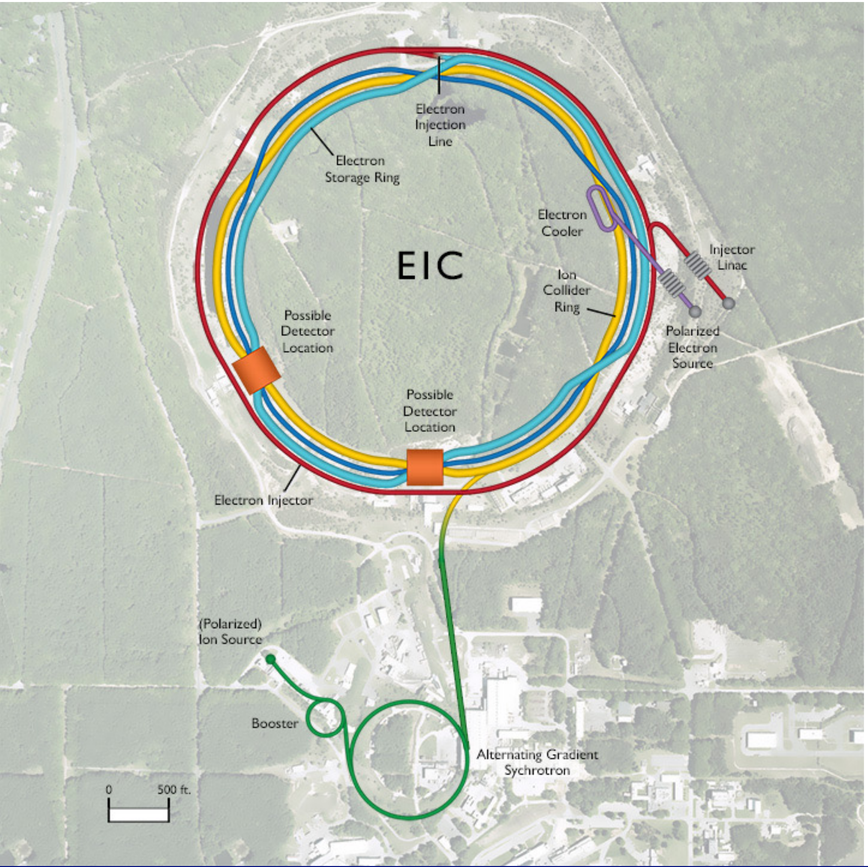

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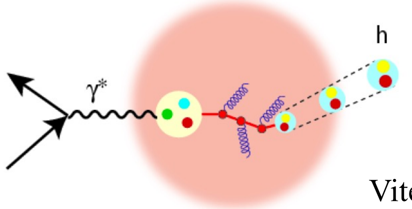
- Parton structure of nucleons
- Parton distribution function modifications
- QCD energy loss

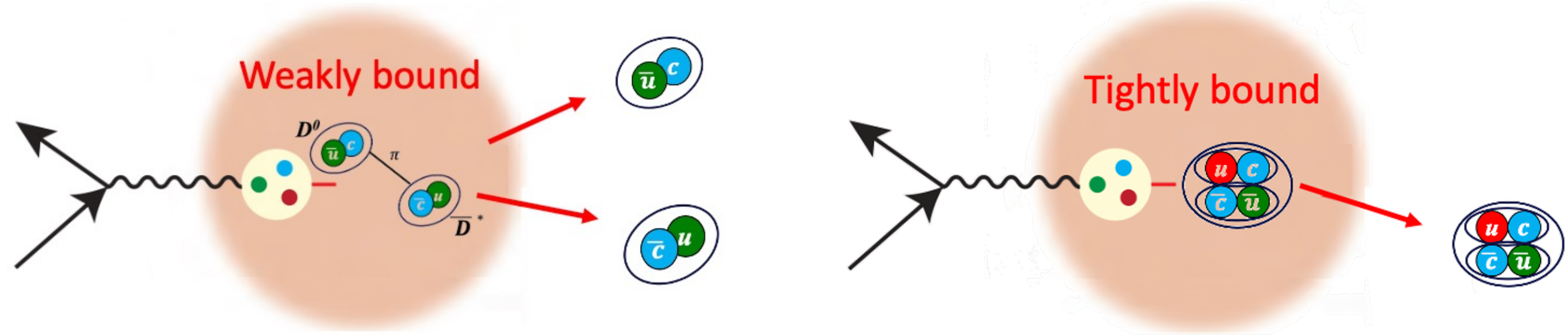
Hadronization inside the nucleus becomes important



Vitev, 1912.10965

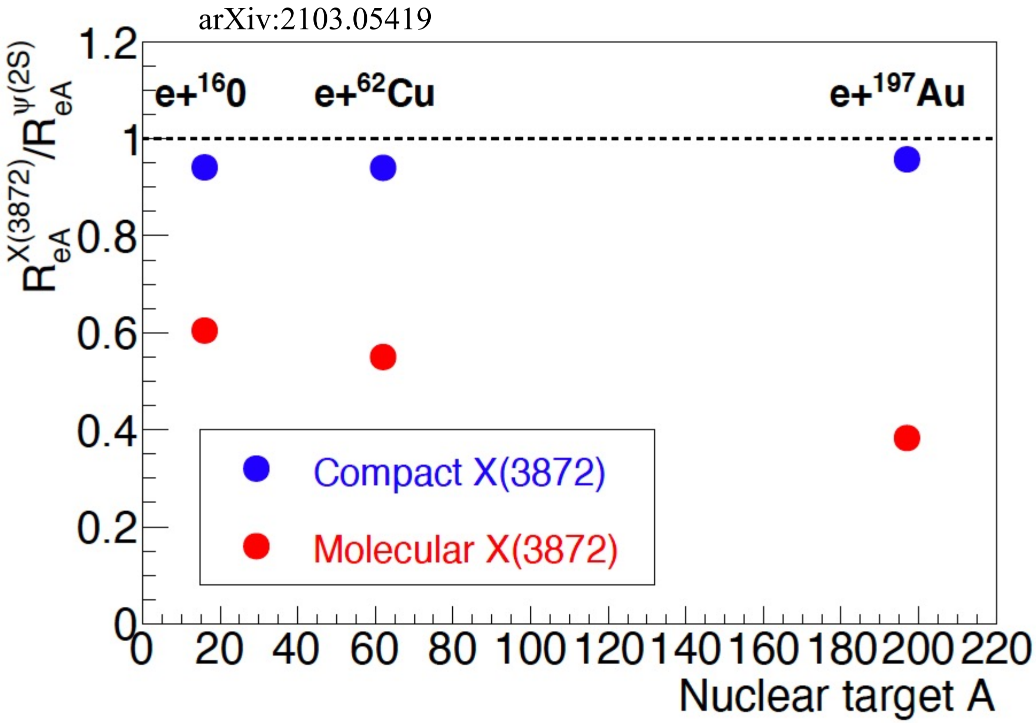
Filtering States with the Nucleus

- Quarkonia is subject to breakup as it crosses the nucleus – suppression due to disruption of the $Q\bar{Q}$ pair



- Larger (weakly bound) states sample a larger volume of the nucleus while passing through – larger absorption cross section Arleo, Gossiaux, Gousset, Aichelin PRC 61 (2000) 054906
- Explains trends observed in fixed target data at FNAL, SPS
- Test idea via MC simulation of propagation through nucleus for three cases:
    - $\psi(2S)$ with radius 0.87 fm, compact X(3872) with radius 1 fm, molecular X(3872) with radius 7 fm

Relative modification of X(3872)/ $\psi(2S)$ at EIC



$$\frac{R_{eA}^{X(3872)}}{R_{eA}^{\psi(2S)}} = \frac{\sigma_{eA}^{X}}{\sigma_{eA}^{\psi}} \Bigg/ \frac{\sigma_{ep}^{X}}{\sigma_{ep}^{\psi}}$$

- **Little difference in suppression between model of compact X(3872) and $\psi(2S)$, as expected.**
- **Large difference between model of molecular X(3872) and $\psi(2S)$.**

X(3872) is only an example, model equally applicable for other exotics accessible at EIC

Summary

- Hadron spectroscopy is a thriving field. Quark model is expanding.

- Interactions of exotics with other particles give us new ways to probe and constrain their structure that cannot be accessed in B-decays

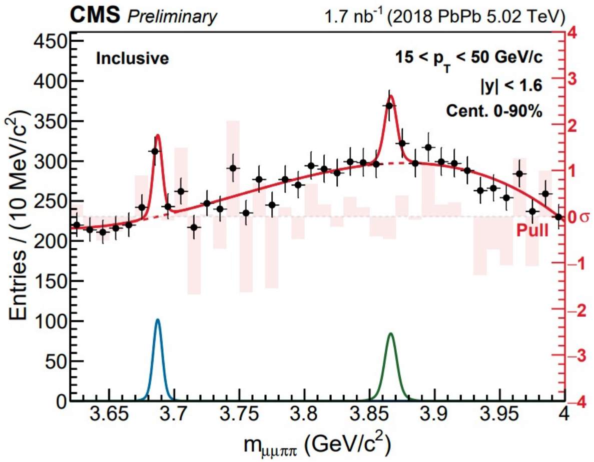
- Multiple future experimental facilities are on the horizon.

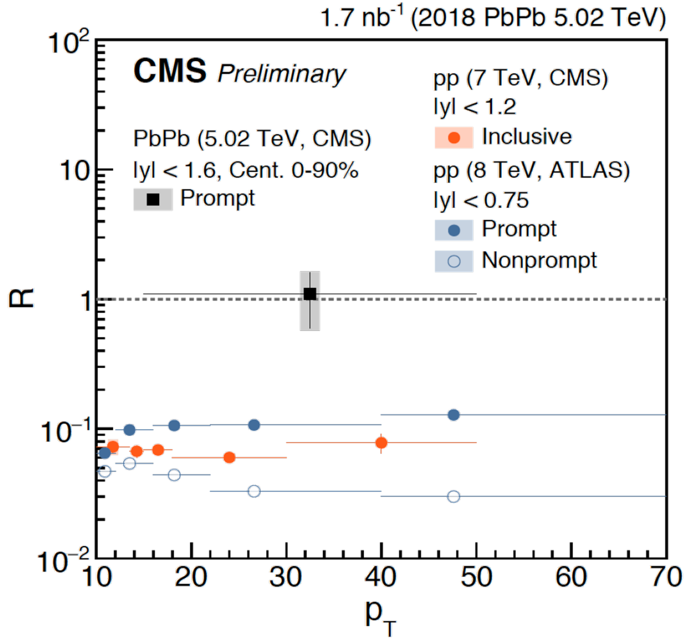
Los Alamos is supported by the US Dept. of Energy/Office of Science/Office of Nuclear Physics

BACKUPS

Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005





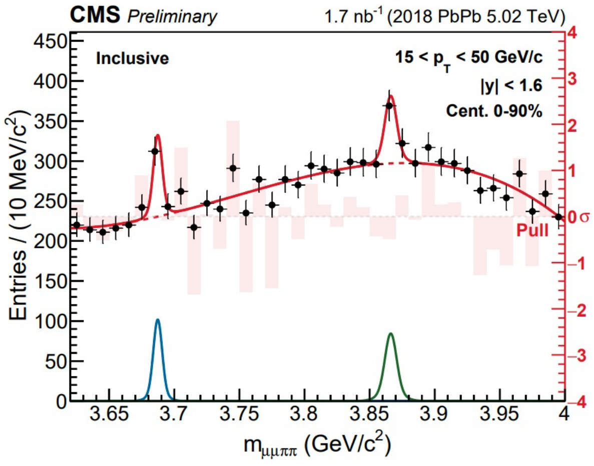
Recombination of X(3872) at pT > 15 GeV?

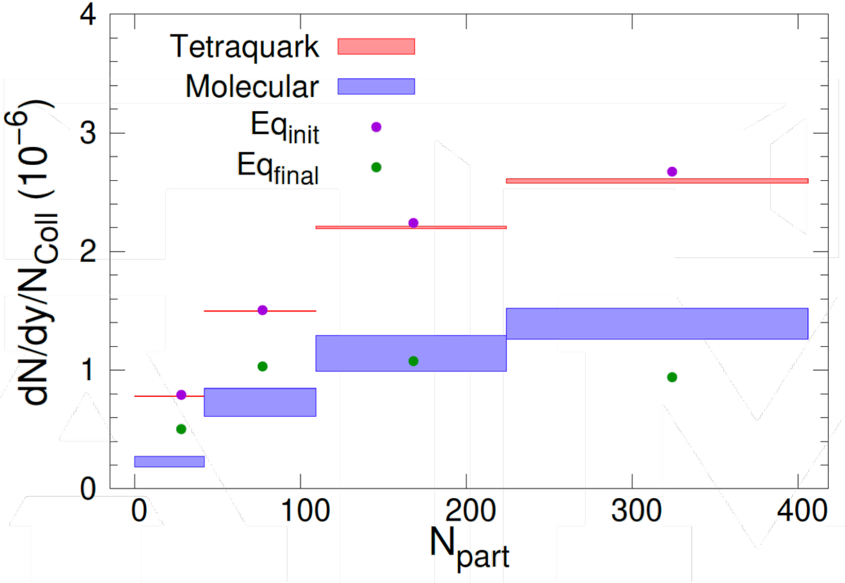
Prompt X(3872)/ ψ(2S) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV

Prompt X(3872)/ ψ(2S) ≈ 0.1 in pp at 8 TeV

Exotic X(3872) in dense medium (PbPb)

CMS-PAS-HIN-19-005





Transport model gives larger yield for compact tetraquark vs. molecule by factor of ~2 in PbPb

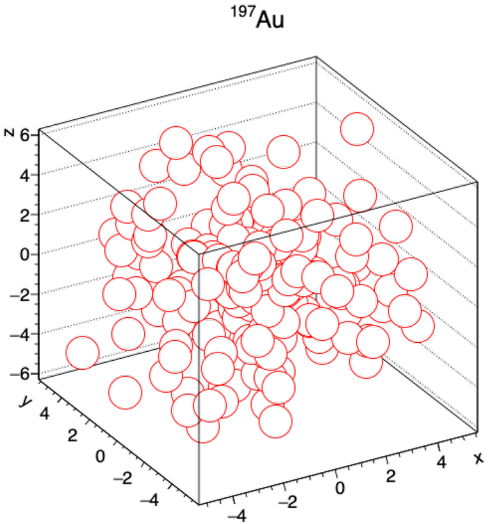
Will be tested with future PbPb data sets.

Prompt X(3872)/ ψ(2S) = 1.10 ± 0.51 ± 0.53 in PbPb at 5 TeV

Prompt X(3872)/ ψ(2S) ≈ 0.1 in pp at 8 TeV

Intriguing data! Inconclusive with these uncertainties.

Propagation through Nuclei



- In Monte Carlo simulation, populate a Glauber nucleus, using parameters from PHOBOS model: arXiv:1408.2549
- Randomly select starting point for $Q\bar{Q}$ pair
- Propagate $Q\bar{Q}$ along z axis

- Following model of Arleo *et al.* in Phys Rev C, 61 054906 (2000), expand $Q\bar{Q}$ radius as a function of time:

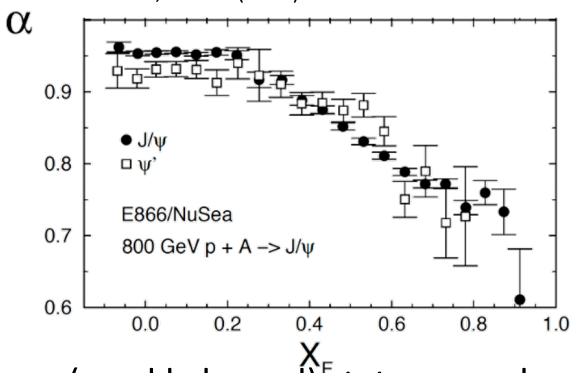
$$r_{c\bar{c}}(\tau) = \begin{cases} r_0 + v_{c\bar{c}}\ \tau & \text{if } r_{c\bar{c}}(\tau) \leqslant r_i \\ r_i & \text{otherwise} \end{cases}$$

- Calculate radius-dependent cross section: $\sigma_{(c\bar{c})_1 N} = \sigma_{\psi N}(s) \cdot (r_{c\bar{c}}/r_{\psi})^2$
- If the state comes within a distance of $\sqrt{\sigma_{c\bar{c}}/\pi}$ to a nucleon, consider it disrupted.
- Three cases: $\psi(2S)$ with radius 0.87 fm, compact X(3872) with radius 1 fm, molecular X(3872) with radius 7 fm

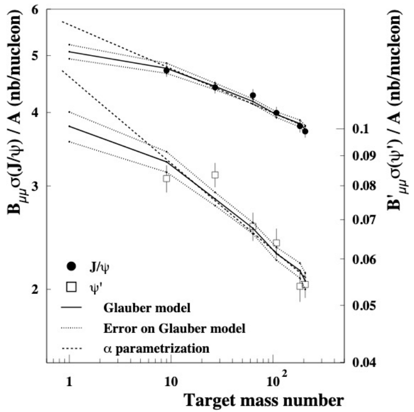
Filtering States with the Nucleus

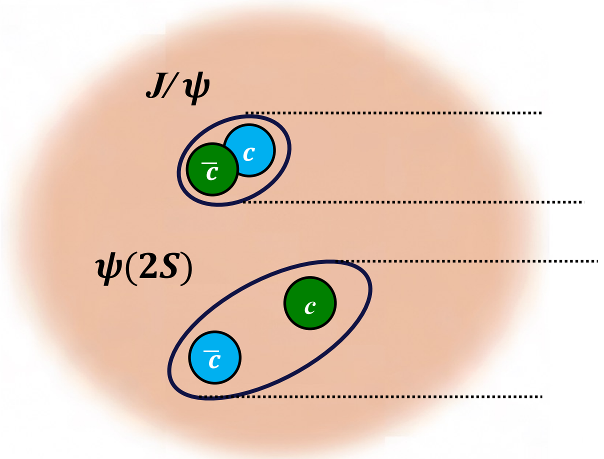
- At the EIC, hadronization inside the nucleus becomes an important effect (Vitev, 1912.10965)
- Quarkonia is subject to breakup as it crosses the nucleus – suppression due to disruption of the $Q\bar{Q}$ pair

E866, PRL 84 (2000) 3256-3260



NA50, EPJC 48 329 (2006)





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- Explains trends observed in fixed target data at FNAL, SPS
- As expected, fails at RHIC (hadronization occurs outside nucleus) PHENIX PRL 111 202301 (2013)

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Table 1: Charmonium states and binding energies

Satz hep-ph/0512217

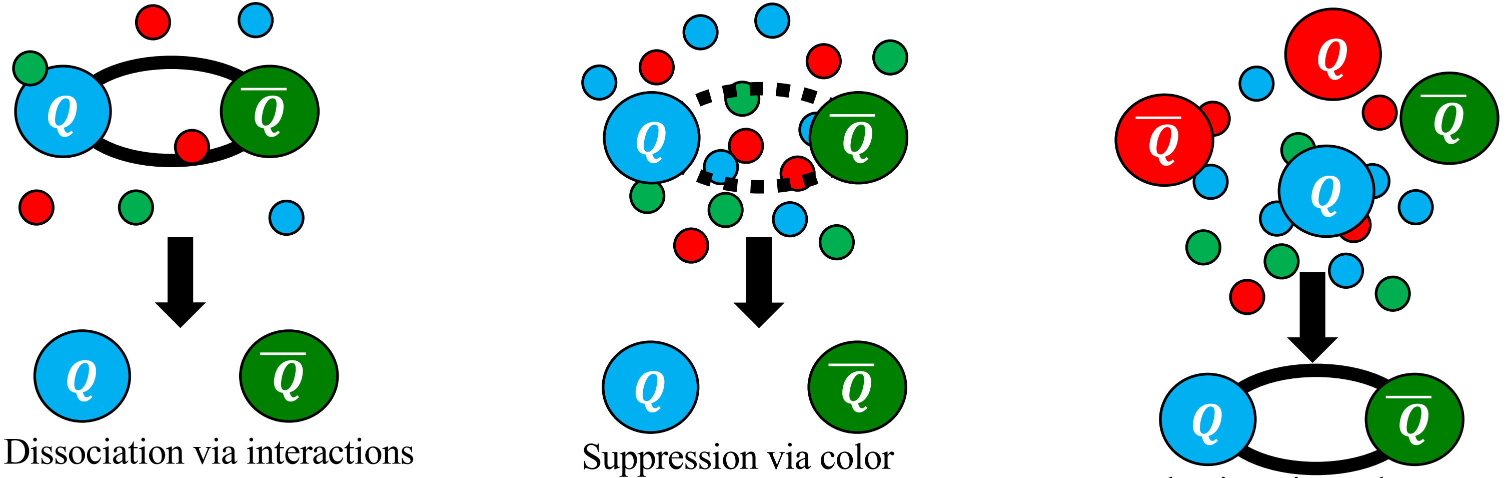
state	Υ	χ_{b0}	χ_{b1}	χ_{b2}	Υ'	χ'_{b0}	χ'_{b1}	χ'_{b2}	Υ''
mass [GeV]	9.46	9.86	9.89	9.91	10.02	10.23	10.26	10.27	10.36
ΔE [GeV]	1.10	0.70	0.67	0.64	0.53	0.34	0.30	0.29	0.20

Table 2: Bottomonium states and binding energies

Quarkonia in the QCD medium

Diffuse medium (pp,pA) → Dense medium (pA, AA)

Increasing T, $N_{charged}$



Dissociation via interactions with comoving particles

Suppression via color screening

Production via coalescence

Experimentally, we use different collision systems/kinematic regions to prepare environments where different non-perturbative effects dominate.

Separate prompt/non-prompt production

Simultaneous fit to mass and proper time in each multiplicity bin